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Precursor Science for the Terrestrial Planet Finder

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Abstract

This document outlines a path for the development of the field of extrasolar planet research, with a particular emphasis on the goals of the Terrestrial Planet Finder (TPF). Over the past decade, a new field of research has developed, the study of extrasolar planetary systems, driven by the discovery of massive planets around nearby stars. The planet count now stands at over 130. Are there Earth-like planets around nearby stars? Might any of those planets be conducive to the formation and maintenance of life? These are the questions that TPF seeks to answer.

TPF will be implemented as a suite of two space observatories, a 6-m class optical coronagraph, to be launched around 2014, and a formation flying mid-infrared interferometer, to be launched sometime prior to 2020. These facilities will survey up to 165 or more nearby stars and detect planets like Earth should they be present in the ‘habitable zone’ around each star. With observations over a broad wavelength range, TPF will provide a robust determination of the atmospheric composition of planets to assess habitability and the presence of life.

At this early stage of TPF’s development, precursor observational and theoretical programs are essential to help define the mission, to aid our understanding of the planets that TPF could discover, and to characterize the stars that TPF will eventually study. This document is necessarily broad in scope because the significance of individual discoveries is greatly enhanced when viewed in the context of the field as a whole. This document has the ambitious goal of taking us from our limited knowledge today, in 2004, to the era of TPF observations in the middle of the next decade. We must use the intervening years wisely.

This document will be reviewed annually and updated as needed. The most recent edition is available online at <http://tpf.jpl.nasa.gov/> or by email request to lawson@huey.jpl.nasa.gov.

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Executive Summary

Our understanding of planetary systems has undergone a profound shift in the past several years. The field has been transformed from one in which speculation, educated guesses, and extrapolation from a single studied example (our own Solar System) have been abruptly replaced by the empirical wealth of over 130 discovered planets distributed among more than 115 different planetary systems, with several new giant planets being found every month. Yet these discoveries just reveal the tip of the iceberg. If our Solar System is typical, then these giant planets may be accompanied by many sibling terrestrial planets.

The sheer variety of planetary systems — including hot Jupiters, eccentric giants, and resonance-locked pairs — has come as a surprise. The current situation is perhaps analogous to the time during which Tycho Brahe was accumulating planetary observations of unprecedented accuracy, but before Kepler's synthesis of the laws of planetary motion and Newton's discovery of universal gravitation.

The Terrestrial Planet Finder (TPF) is the cornerstone of NASA's Navigator program. The objectives of the TPF missions are simply stated:

- To search for and detect terrestrial planets that might exist in the habitable zones of nearby stars.
- To characterize the atmosphere of planets it detects and search for indicators of the presence of life.
- To undertake a program of comparative study of all constituents of planetary systems.

TPF is envisaged as a series of two space observatories: a 6-m class optical coronagraph (TPF-C), to be launched around 2014; and a mid-infrared formation-flying interferometer (TPF-I), to be developed as a collaboration with the European Space Agency and launched sometime prior to 2020.

Decisions concerning the nature and scope of TPF will be guided by both scientific considerations and technological readiness. TPF requires a program of precursor observational and theoretical activities for a variety of reasons: to provide the astronomical information needed to assist in decisions concerning the architecture of its missions; to specify the most promising spectral markers for characterizing planets and detecting signs of life; to determine the volume of space that will be searched; and to characterize TPF target stars. In addition, NASA and the TPF Project must ensure that a robust science community with a broad scientific understanding of the formation and evolution of planetary systems is prepared to plan and interpret TPF observations.

Precursor science programs are critical to our growing understanding of how planetary systems, terrestrial planets, and abodes of life like our own form and evolve. They are also directly relevant to the planning and implementation of technology for TPF. In this sense *Precursor Science for the Terrestrial Planet Finder* is a companion document to the *Technology Plan for the Terrestrial Planet Finder*. Results of

precursor science programs will influence the design and scope of TPF missions and lay the foundation for the next decade of research relevant to the search for life on other worlds.

This document represents a broad consensus of the science community on the areas of scientific importance that support the goals of TPF. This science community is worldwide. Of particular note is the collaboration between NASA and ESA on the joint scientific objectives of TPF and the Darwin mission. This document is intended to be inclusive of the Darwin science goals and the precursor science efforts in Europe and worldwide.



Figure 1. Overview of TPF precursor science themes and programmatic objectives.

The most important challenges for precursor science activities for TPF are illustrated in Fig. 1 and are as follows:

1. To assess or better constrain the characteristics of extrasolar planetary systems, and to better estimate the fraction of stars with terrestrial-sized, potentially habitable planets. TPF has perhaps the most technically challenging missions of any planned in space science. These missions are defined in scope, complexity, cost, and scientific return by the sensitivity and angular resolution required to search for planets. Our understanding of the characteristics of extrasolar planetary systems will determine many of the key design parameters of the missions.
2. To determine the prevalence of dust disks around other stars and how it will influence the mission design. Exozodiacal dust may serve as a signpost for the presence of planets, and yet may also degrade the ability of a TPF mission to detect planets. The amount of exozodiacal emission may be an important discriminator between some interferometric and coronagraphic designs and so

must be well understood prior to the Mission Concept Reviews at the entry of a project's Phase A. Thus, in this document, considerable emphasis is placed on robust determination of the amount of exozodiacal emission around potential TPF targets through observations with both space-based and ground-based telescopes.

3. To perform a thorough, systematic, and comprehensive study of potential TPF targets, including observations using ground-based and space-based observatories. The TPF target lists will be observed, discussed, and refined for many years, beginning now and extending into the start of observations.
4. To determine the biomarkers and other observable properties of habitable Earth-like planets that will drive the mission design. The specific biomarkers susceptible for observation by TPF at relatively low spectral resolution at optical and infrared wavelengths have been discussed in the community over many years. There is broad agreement that visible and mid-IR observations provide exciting and powerful diagnostics of habitability and even of life itself. Continued evaluation and modeling is crucial, because the interpretation of planetary spectra is the key to characterizing any planets that are detected.
5. To continue to build the community infrastructure, including appropriate data archives, as well as increased support for graduate and postdoctoral fellowship programs centered on the science projects relevant to TPF. In addition to specific projects of direct relevance to the design or scope of the missions, the TPF Science Working Group emphasizes that a vigorous program of theoretical and observational investigations relevant to TPF is vital to building a cadre of scientists ready to exploit observations of extrasolar planets.

Guided by the above challenges, the scientific recommendations are organized into four major research areas:

Characteristics of Extrasolar Planetary Systems

Exozodiacal Dust and the Search for Planets

Characteristics of Stars That May Harbor Earth-Like Planets

Characteristics of Planets That May Support Life

This document presents a multidisciplinary approach to preparing the way for TPF. It reflects the breadth and diversity of the growing field of the study of extrasolar planetary systems. For TPF, we must be sure that we are posing the scientific questions correctly, and that we will be able to interpret the results that TPF will deliver. No single observing method or numerical model provides the whole story, so the approach laid out proposes many interlocking, interdisciplinary studies. Taken together, they lay the foundation for an entirely new field of scientific endeavor for the Twenty-First century: the exploration of planetary systems in our solar neighborhood — their physical, chemical, and biological properties; and their formation and evolution.

In addition to laying out a program of scientific research that supports TPF and helps to define the missions, this document serves a *programmatic* purpose. For NASA, the missions that are developed in a given discipline must complement each other in terms of scientific priorities, necessary scientific precursors, technological maturity, and available budget. Within these pages, specific scientific needs for TPF are referenced to missions that are currently flying or under development. Although the programmatic

considerations for TPF-C and TPF-I are identical, it should be kept in mind that their schedules will lag by approximately five years. In the description of programmatics included here, missions related to TPF are only referenced to TPF-C. The over-riding schedule for TPF precursor science is driven by TPF-C because of its earlier launch date.

Table 1 summarizes the key decision points for the TPF project and the missions and instruments that contribute to those decisions. Note that Table 1 represents only the *most critical* missions and instruments for TPF. For the estimation of exozodiacal emission around target stars, overlapping capabilities will be used for a timely entry into Phase A. For the improved understanding of extrasolar planetary systems and an improved estimate of the frequency of Earths, the results from the COROT and Kepler missions will be used in combination with extrapolation from steadily improving radial-velocity datasets.

Table 1. Key Missions and Scientific Contributions to TPF Precursor Science*

Instrument / Mission	Science Contribution	Programmatic Gate for TPF-C	Science Theme
Activities During TPF-C Pre-Phase A <i>Emphasis on Mission Concept Review</i>			
Spitzer	IRS/MIPS survey of ~250 stars for exozodiacal dust at >5 AU	Phase A	Exozodi
Keck-I, LBT-I, VLTI	Warm dust (10 μm) for ~150 stars for exozodiacal dust at 0.5–2 AU	Phase A	Exozodi
Radial velocity monitoring	Detect planets of Saturn mass or less at 2–5 AU to help refine the incidence of low mass planets	Phase B	Planetary Systems
COROT/MOST	Transits of planets of 8–10 Earth mass at <0.5 AU to help refine incidence of low mass planets	Phase B	Planetary Systems
Theory/modeling	Estimate of frequency of Earth-like planets based on giant planets detected by radial velocity or other techniques	Phase B	Planetary Systems
Theory/modeling	Refine spectral signatures to be searched	Phase A	Biomarkers
Activities During TPF-C Phase A <i>Emphasis on Scientific Scope of the Mission</i>			
Kepler	Statistics of Earth-like planets (transiting) to determine incidence of low-mass planets	Phase B	Planetary Systems
Activities During TPF-C Pre-Phase A to Phase E <i>Emphasis on Development of Target List</i>			
SIM	Detect potential TPF target systems by finding planets around nearby stars with masses as low as a few Earth-masses.	—	Target List
JWST/HST	Images of TPF target fields $R > 30$ mag; $F_{\nu}(8 \mu\text{m}) < 1 \mu\text{Jy}$	—	Target List
Spitzer/Interferometers/ Herschel/SOFIA	Characterize exozodiacal emission of potential targets	—	Exozodi, Target List

* This table highlights the missions most relevant to TPF amongst those listed in Table 12

As the individual chapters show, there are numerous research areas, many truly multi-disciplinary, which directly relate to TPF. Each of these areas build a scientific context in which we set the results delivered by the TPF missions themselves. More detailed recommendations are provided in Chapter 8.

Precursor Science for the Terrestrial Planet Finder will be reviewed annually, and with each revision will embody new knowledge and assess progress against the recommendations stated at the end of each chapter. Updates will include an assessment in each of the key areas. This information will be communicated to the Navigator Program management and the Universe Division at NASA Headquarters.

1 Introduction

The work described within these pages has been assembled through the efforts of many astronomers, planetary scientists, technologists, and instrument builders. All share the same vision of striving to answer the important questions that define us culturally and as explorers: “Where did we come from?” and “Are we alone?” The objectives of TPF are echoed in the President’s *Renewed Spirit of Discovery*, whose aims include “Conduct[ing] advanced telescope searches for Earth-like planets and habitable environments around other stars,” and are also explicitly reaffirmed within *The Vision for Space Exploration*, by the NASA Administrator.

Described in this document are the programmatic needs, scientific priorities, and community needs in preparing for TPF.

1.1 Terrestrial Planet Finder: TPF-C and TPF-I

In April 2004, NASA elected to proceed with TPF as a suite of two observatories: a 6-m class optical coronagraph (TPF-C), to be launched around 2014; and a mid-infrared formation-flying interferometer (TPF-I), to be developed jointly with the European Space Agency and launched sometime before 2020. Observations over such a broad wavelength range, from 0.6 to ~ 20 μm , will provide not only a definitive characterization of gross planetary features, but also a robust assessment of habitability and the presence of life.

The proposed TPF program is a bold step that supports *The Vision for Space Exploration* and is well aligned with recommendations of the Decadal Review. This staged approach reduces risk while making data and results available as rapidly as possible. As has been evident over the past few years, TPF technology for both interferometers and coronagraphs has been making excellent progress, promising that TPF-C could be ready for launch as soon as 2014. Collaborations with the European Space Agency (ESA), which have emphasized common science goals for TPF and Darwin, were expanded in 2003 to explore the most promising interferometer designs. Also under discussion in 2004 is the possibility of a collaborative formation flying demonstration, to be conducted through the ESA SMART-3 mission for launch as soon as 2012.

Plans for the immediate future therefore include continued technology development for both TPF-C and TPF-I, enhancing ties with ESA, and preparing TPF-C for entry into Phase A.

1.2 Programmatic Decisions

This document is structured to resolve questions that are of programmatic importance to the development of TPF. Although TPF-C will be launched prior to TPF-I, and will therefore follow a different schedule, the programmatic concerns for both TPF-C and TPF-I are essentially the same. The development of each is therefore shown schematically by the single illustration in Fig. 2 and described below:

- a. In Pre-Phase A, the focus of TPF precursor science will be to contribute to the Mission Concept Review that will allow a TPF mission to enter Phase A of its project lifecycle. Key questions will include: the level of exozodiacal emission and its influence on the designs of interferometer or coronagraph architectures; an assessment, mostly complete, of the spectral markers for TPF; and an initial selection of appropriate target stars.
- b. In Phase A, the mission and system definition studies will refine the architecture so that it is ready for preliminary designs in Phase B. The over-riding question to be resolved by the end of Phase A will be to define the capability of the mission and determine to what scale the observatory must be built. What volume of space should be searched for planets? How large of a collecting area will be needed? What angular resolution will be required? Scaling the architecture and defining the scope of the mission will be necessary before either TPF-C or TPF-I continue to Phase B, C, and D.

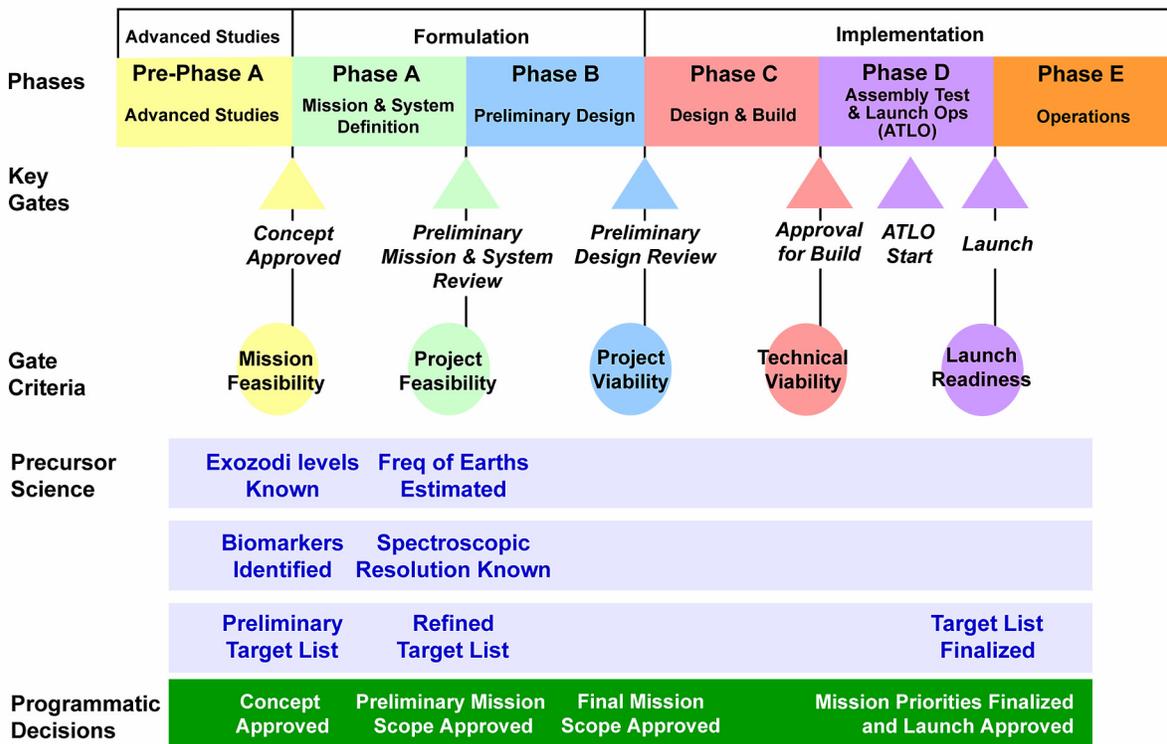


Figure 2. TPF summary schedule. This synoptic schedule shows the major events in the life cycle of TPF, including the key science questions that must be addressed, and in which phase of the development the answers are needed. The most important near-term science goal is to assess the level of exozodiacal light in potential TPF targets. This will assist in the mission concept review, prior to the entry into Phase A, as described in Chapter 4.

- c. In Phase B, C, and D, precursor science will emphasize the preparation of a mission whose capability is already well defined. Studies will emphasize further development of the target list, understanding the environment of the target stars, and determining the best strategy to maximize the scientific return of the mission.

In the sections below, we show how these scientific questions feed directly into the decisions that TPF-C and TPF-I face during their development.

Emphasis in Pre-Phase A: Mission Concept Review

TPF-C and TPF-I are currently in the first (or pre-Phase A) stage of the NASA Project Life Cycle, shown in Fig. 2, and are undertaking a suite of technology development projects to demonstrate technological readiness leading to their Mission Concept Reviews.

Exozodiacal Light Levels: For the coronagraph and interferometer designs, the driving requirement in each architecture is the need to suppress or reject starlight so that planet light can be detected. Moreover, atmospheric spectroscopy must be possible within the bands of biomarkers that have been identified. The TPF Project has estimated that starlight rejection of $\sim 10^9$ – 10^{10} :1 is necessary for optical coronagraphs, and $\sim 10^5$ – 10^6 :1 for mid-infrared interferometers. In both cases the contrast ratio has been estimated based on an assumed brightness ratio of the star and planet. Previous architecture studies have shown that the brightness of dust in the habitable zone of the target star adversely affects the integration time necessary to detect planets for both the coronagraphic and interferometric systems, but with a somewhat greater effect for interferometers. Thus, in addition to a critical assessment of the technology needed for the two architectures, it is important to characterize and understand the brightness of the average exozodiacal emission surrounding potential TPF targets prior to the Mission Concept Review.

Biomarkers: The technical requirements for the architectures of both coronagraphs and interferometers are dependent upon the wavelength range, or spectral bandpass, that is necessary to detect evidence of life. In particular, the shortest operating wavelength determines the required surface smoothness of optics and the mechanical stability of the observatory. The need for better starlight suppression would push the designs to use longer wavelengths, but amongst mid-infrared biomarkers the relatively short-wavelength water-vapor band at 6.3 μm may prove the most sensitive and easiest to interpret — forcing a tightening of requirements of a mid-infrared interferometer design. The necessary spectral bands of visible and mid-infrared biomarkers must be known if the design teams are to provide instruments tailored to TPF’s needs.

Preliminary Target List: The quality of science that will be derived from TPF will be partly determined by the stars included in the final target list. A preliminary list of stars will greatly assist in judging the technical feasibility of the mission concepts. This preliminary target list may include a larger number of stars than are retained in the final list.

Emphasis in Phase A: Determining the Scope of a Mission

In Phase A the emphasis will be on specifying the detailed design of the optics of each TPF observatory, TPF-C or TPF-I, leading to the Preliminary Mission and System Review. The science issues relevant to the design of the optics in each case are as follows:

Frequency of Earths: The TPF missions will be capability-driven missions. The scale of the observatories — the size of the coronagraph primary optics or distance between the furthest collecting apertures of the interferometer — will determine the number of stars that are attainable by each mission. Defining the capability of a mission will involve a trade between the desire to explore a larger number of extrasolar planetary systems and the technological difficulty of building a larger observatory. To better understand this trade, precursor science activities *prior* to entry to Phase A will include detections of gas giant planets by a variety of techniques. Coupled with advances in astrophysical theory, these data (including perhaps transit detections of several-Earth mass planets from COROT or MOST) will provide improved estimates of the frequency of Earth-like planets. The programmatic implications will be wide-ranging. More certain knowledge of the frequency of Earths will not only help set the scale of the observatories but will later assist in setting priorities in the initial phases of the missions.

Spectroscopic Resolution: In Phase A the details of the spectrometers, filters, dichroics, and operating wavelengths of various instruments within a TPF facility will need to be defined. The instruments will be optimized for the detection of known biomarkers. Our understanding of biomarkers must have advanced sufficiently during Phase A to set requirements for the detailed instrument designs.

Refined Target List: All nearby stars should be well characterized before the target lists for TPF can be chosen. A refined target list, with the furthest target identified, will be needed in Phase A to set the scale of the observatory. The distance to the furthest planet in the survey will be determined by the size of the observatory (its angular resolution) and the area of its collecting apertures (its sensitivity).

Emphasis in Phase B, C/D: Setting the Mission Priorities

Up until launch, precursor science activities will aid in preparations for each mission: undertaking complementary observations of the target stars, establishing data-bases of standardized measurements, and refining techniques for the detection of biomarkers. There will be a wide variety of activities focused on improving the scientific productivity of the missions.

Moreover, throughout the formulation and development of TPF, it is important to develop the scientific community who will be the ultimate users of the TPF missions.

Target List: During the period leading up to the launch of TPF-C and TPF-I, their target lists will be finalized. This will involve the continuation of a coordinated program to observe and characterize all potential target stars and to establish a standardized database and archive of measurements. The target lists will be refined and prioritized to identify target stars most likely to harbor Earth-like planets. Observations with the Space Interferometry Mission (SIM) will be a particularly important component of this final step of characterization.

1.3 Organization of this Document

In Chapter 2, *Overview of TPF Science*, the high-level science objectives for TPF are defined. For the optical and mid-infrared wavebands currently under study, the needed resolution, sensitivity, and spectral coverage are defined in term of the biomarkers that extrasolar Earth-like planets may exhibit.

The four succeeding chapters are ordered to reflect the long-term priorities (Pre-Phase A through launch) of precursor science, and cover the major research themes that directly feed into TPF:

Chapter 3: *Characteristics of Extrasolar Planetary Systems*

Chapter 4: *Exozodiacal Dust and the Search for Planets*

Chapter 5: *Characteristics of Stars That May Harbor Earth-Like Planets*

Chapter 6: *Characteristics of Planets That May Support Life*

These topics require multi-disciplinary observations as well as a theoretical framework to help interpret the data and extrapolate them to specific TPF needs. Numerical modeling provides a means of challenging our theoretical framework with the observations. Accordingly, observation, theory, and modeling are presented in parallel, to emphasize the interdisciplinary nature of this research.

Chapter 7, *Development of TPF Precursor Science*, shows how the different elements of the proposed research work together to further the objectives TPF precursor science. These elements include TPF Foundation Science, community infrastructure for interdisciplinary theoretical research, complete, accurate and user-friendly databases, and new technology for instruments and missions.

Finally, we summarize in Chapter 8 our *Priorities and Recommendations* for developing precursor science, with a schedule for research milestones that support TPF, and the budget resources necessary to achieve them. We also show how ground and space missions — those currently observing, and those scheduled to be in operation in the next several years — will contribute to TPF precursor science.

Chapter 8 also includes recommendations for ancillary precursor science that would broaden and enrich the range of activities described in earlier chapters. Although such individual topics may not directly address the questions outlined above, they contribute strongly to the development of the field of extrasolar planet research — a field still in its infancy. It would be a mistake to focus too narrowly on only the big questions or the expected outcomes of individual activities. In much of astronomy serendipitous discoveries can take a field in unexpected directions, and the correct interpretation of individual results demands that the results be viewed in a broad framework. These related activities build a tapestry of research results that bring together diverse threads into a coherent whole.

At the end of this document, we acknowledge the many contributors, and provide an acronym list, and suggestions for further reading.

2 Overview of TPF Science Characterization of Other Solar Systems and the Search for Life

Signposts of habitability and of primitive life exist at both optical/near-infrared and mid-infrared wavelength bands, and taken as a whole the combined missions of TPF-C and TPF-I will provide more compelling scientific results than either mission could provide by itself. Measurements taken over both bands will detect a wider range of biomarkers and yield a robust and definitive assessment of a planet's habitability. Observations at optical and mid-infrared wavelengths will confirm detections and extend interpretations that might only have been made initially at one wavelength. The two missions are complementary, and the scientific planning for the two will be done concurrently and at an early phase of their development.

This Chapter summarizes the objectives of TPF as defined by the TPF Project and the TPF Science Working Group, with additional inputs from the broader scientific community. It is important to clearly state the objectives for TPF so as to provide a context and motivation for the precursor science program that is laid out in the remainder of this document.

2.1 Summary

One of the most profound questions that modern science can address is whether or not Earth-like planets, habitable or already life-bearing, exist elsewhere in the Universe. Thus, a defining goal of NASA's Navigator program is to understand the formation and evolution of planets and, ultimately, of life beyond our Solar System. This goal requires a complete census of planets orbiting nearby stars down to the mass of the Earth; an understanding of the physical and biological processes that make a planet habitable and that might lead to the evolution of a "living" planet; and the direct examination of nearby planets for signs of life. With these objectives in mind, we define the primary goal for TPF as follows.

TPF-C and TPF-I must be capable of detecting radiation from Earth-like planets located in the habitable zones around a minimum of 35 and preferably 165 or more solar type stars — having spectral types F, G, and K. TPF observatories must be capable of determining the orbital and physical properties of detected planets to assess their habitability, but most importantly be capable of characterizing the atmospheres and searching for potential biomarkers among the brightest Earth-like candidates.

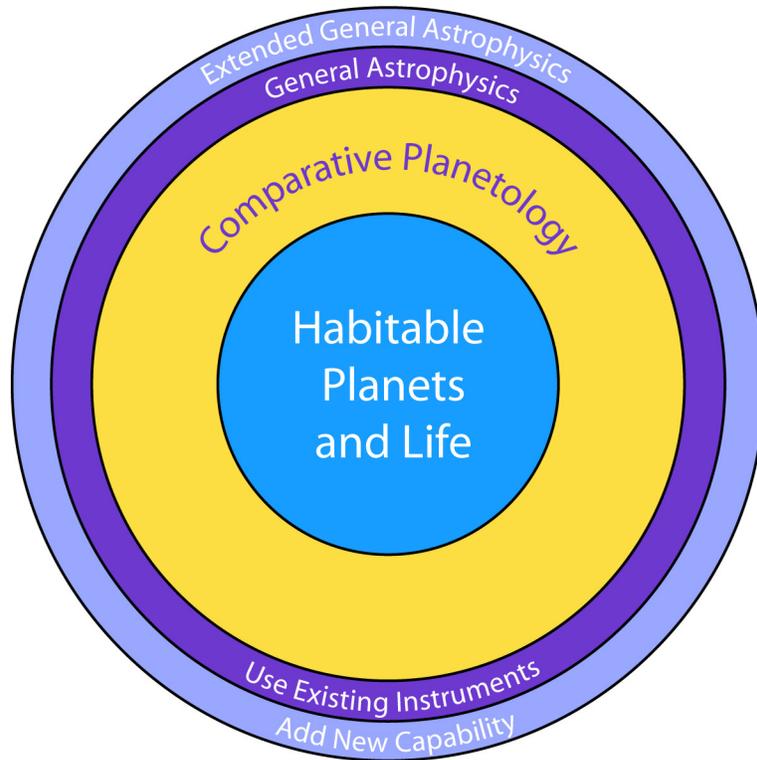


Figure 3. Schematic of the scientific goals of the Terrestrial Planet Finder. The core science of TPF is to directly detect and characterize Earth-like planets should they be present in the habitable zones around the nearest stars. TPF will also be capable of conducting studies in comparative planetology, and with little or no additional cost of undertaking observations of general astrophysical interest.

Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, e.g. both gas giant and terrestrial planets, and debris disks. Some of this information, such as the properties of debris disks and the masses and orbital properties of gas giant planets, will become available with currently planned space or ground-based facilities. However, the spectral characterization of most giant planets will require observations with TPF-C and TPF-I. The ability to carry out a program of comparative planetology across a range of planetary masses and orbital locations in a large number of new solar systems is by itself an important scientific motivation for the missions.

An observatory with the power to detect an Earth orbiting a nearby star will be able to collect important new data on many targets of general astrophysical interest. Such ancillary science might use either the existing planet-finding instruments or possibly additional instruments — providing they were provided at little or no additional cost to the overall mission. The hierarchy of science goals is summarized in Fig. 3.

2.2 Properties of Target Stars

TPF-C and TPF-I will focus its search to Sun-like and similar stars, broadly defined as those main-sequence stars with spectral types F, G, and K, either in single systems or wide binaries. A few nearby A, early F and M stars may be considered in addition to the primary solar-type targets. The majority of stars earlier than G on the target list should be restricted to spectral types F5–F9. In this way, the sample will be strongly focused on stars similar to the Sun. M-dwarfs closest to our Solar System (having habitable zones with the largest angular sizes) should also be considered candidates for TPF searches.

TPF-C and TPF-I will be designed so that, with a high degree of confidence, they will be capable of detecting Earth-like planets should they exist in the habitable zones of the stars in their survey. The angular resolution, and therefore the physical size of each observatory, will be chosen to accommodate the most distant stars in their surveys. Obviously, missions that must survey more stars must be more capable — primarily in sensitivity and angular resolution. How many stars should be surveyed? We can make a preliminary estimate of the survey size based on the estimated fraction of stars with Earth-like planets in their habitable zone, which we will call η_{\oplus} .

Preliminary evidence suggests that η_{\oplus} is approximately 10%. Of the 300 best-studied F, G, K, and M main-sequence stars surveyed by the Lick Observatory planet search, 15% were found to have gas-giant planets with semi-major axes less than 3 AU. If smaller planets are as common as larger planets, one might expect to find roughly the same number of terrestrial planets within similar orbits.

Based on this assumption, a TPF mission should survey at least 165 stars to have a 90% probability of detecting 15 or more terrestrial planets, or at least 35 stars to have a 90% probability of detecting at least 3 planets. In Pre-Phase A, the designs of the optics for a mission will be scaled based on a preliminary estimate of η_{\oplus} , relying upon the latest available data, which will need to be refined prior to TPF-C or TPF-I entering Phase B of its life cycle.

2.3 Search Region Around Target Stars

The habitable zone is defined as that region around a star within which, instantaneously, liquid water may exist. A planet located in the habitable zone is in principle habitable by water-based life like our own. The continuously-habitable zone is the narrower range for which liquid water and hence habitability continues for geologically significant timescales, considered here to be a billion years or more. The continuously-habitable zone must be defined in this way principally because main sequence stars brighten monotonically with time as hydrogen is converted to helium. As illustrated in Fig. 4, the location of the habitable zone is a function of stellar type.

For all stars in a survey, a TPF facility should be able to search the potentially habitable region between the orbits of Venus and Mars (0.7 to 1.5 AU) scaled according to the square-root of the luminosity of the specific star in question. All methods of planet detection being considered for TPF purposefully block out the light from the central star, and thus obscure the central portion of the field of view. So as not to overlook planets that may be obscured in the field, the search for planets should include a strategy of optimizing their detection despite the limitations of the field-of-view.

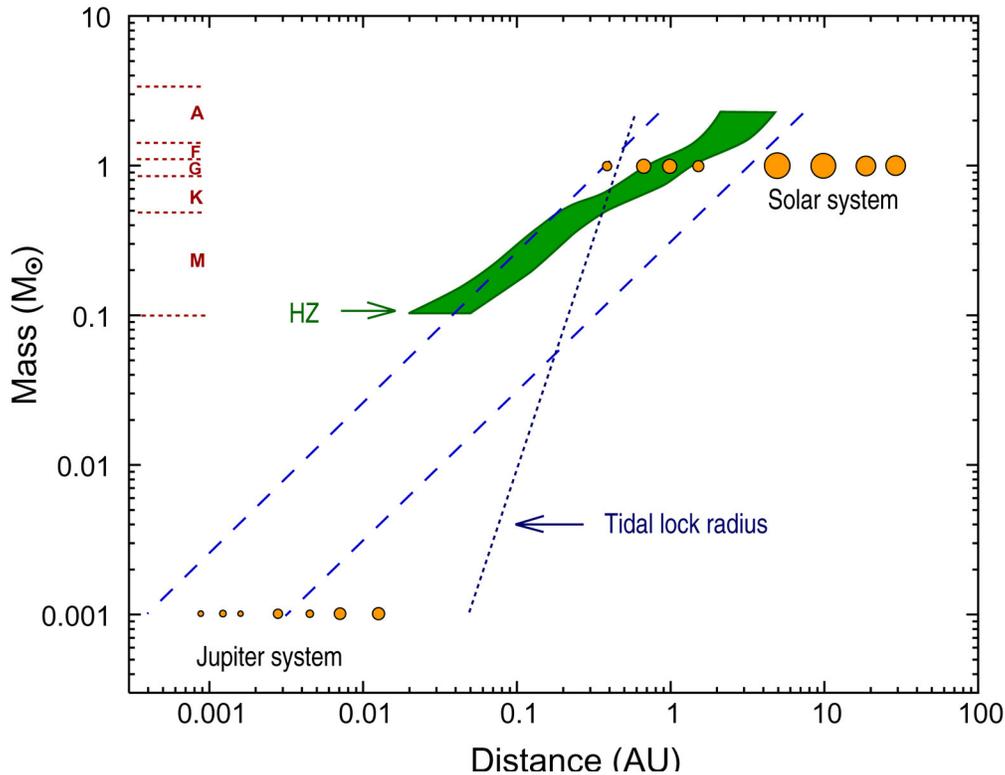


Figure 4. The zero-age main-sequence habitable zone around different types of stars. Eight planets in our Solar System are shown. The long-dashed lines delineate the probable terrestrial planet accretion zone. The dotted line is the distance within which a planet's rotation is predicted to become locked into synchronous rotation within 4.5 billion years as a result of tidal damping.

2.4 Detection and Characterization of Planets

The TPF Science Working group has recommended that TPF missions be designed to detect and characterize terrestrial-type planets around nearby stars, where we define terrestrial-type planets to be Earth-sized objects, with a surface area as small as half the surface area of the Earth. The missions will also detect and take spectra of many giant planets around stars out to at least the orbital location of our own Jupiter. These observations will greatly increase our knowledge of the physical properties of giant planets, their evolution, and their influence on the dynamical environments in which habitable planets may or may not flourish.

TPF-C and TPF-I should be capable of detecting planets even in the presence of zodiacal clouds at a level of up to 10 times the optical depth of the zodiacal cloud in our system. A cloud of orbiting dust due either to debris from asteroid collisions or remnants of comets can be both an important source of information about planetary systems as well as a source of photon noise and potentially confusing emission.

2.4.1 Terrestrial Planets

The principal scientific goal of TPF is to detect directly and to characterize terrestrial-type planets around nearby stars. TPF observatories must be capable of seeing Earth-sized planets in the habitable zones of solar-type stars and analyzing them spectroscopically for signs of life. Terrestrial planets with a surface area at least half as large as the Earth will be considered as Earth-sized. A spectral resolution of 70 would be required at optical wavelengths (0.5–0.8 μm) and a resolution of 20 would be needed at mid-infrared wavelengths (6.5–13 μm). O_2 , H_2O , and O_3 in the visible, or CO_2 , H_2O , and O_3 in the infrared must be measured. Spectroscopic evidence for life is further described later in this chapter.

TPF-C and TPF-I should also be capable of detecting and separately characterizing Earth-like planets in a system in which multiple planets are present. In particular, Earth-like planets should be detectable in the presence of giant planets that may have 10 times the emission of Jupiter.

2.4.2 Gas Giant Planets

The TPF missions should be capable of detecting and characterizing other (non-terrestrial) planets that are found orbiting the target stars. In particular, the missions should be capable of studying bright gas-giant planets at spectral resolution higher than for terrestrial planets since, at comparable distances from their stars, giant planets are 10–100 times brighter than terrestrial planets. For bright gas giants, TPF-C and TPF-I should be capable of spectroscopic measurements with a resolution of $R > 100$. While giant planets are interesting targets unto themselves for spectroscopic study, their presence in a planetary system has deep implications for the existence and fate of terrestrial planets there as well. Their detection in the continuously habitable zone would lead to interesting questions regarding the presence of habitable moons (very difficult or impossible to observe); detection outside the continuously habitable zone would still have implications on the dynamical environment facing terrestrial planets in the continuously-habitable zone. The need to study giant planets generally implies a field of view out to at least 5 AU for the nearest TPF target stars.

2.5 Spectroscopic Evidence for Life

TPF will search for indicators of the presence of life using low-resolution spectroscopy at visible and mid-infrared wavelengths: TPF-C in the visible; and TPF-I in the mid-infrared. Preliminary biomarkers have been identified in both wavelength regimes and can be classified in three categories: convincing evidence of life; probable evidence of life; and input ingredients of life. Although there is no “life molecule,” evidence from these three categories can be used to judge the likelihood of life on a planet. Over the course of the Earth’s history, signatures of life have changed substantially as the Earth’s atmospheric composition and life evolved together. In particular, we have the following possible situations. (a) During the first 40% or so of the Earth’s geologic history, methane and carbon dioxide may have been much more abundant than today. (b) During the last 50% or so of Earth history, molecular oxygen and ozone probably evolved to their high current abundances. (c) Land plant cover may have been abundant during only the most recent 10% of Earth history. (d) Sporadic “icehouse” and “hothouse” episodes may have occurred several times throughout the entire history. Consequently, any potential evidence of life must be assessed within the context of the planetary environment that supports it.

Convincing Evidence of Life

The most convincing spectroscopic evidence for life as we know it is the simultaneous detection of large amounts of molecular oxygen (O_2) and a reduced gas (CH_4 or N_2O) in a planet's atmosphere. We require large amounts of O_2 because pure photochemical processes can produce small amounts of O_2 , as seen for example on Venus and Mars. O_2 , CH_4 , and N_2O are produced in large amounts by the biota (plants, animals, bacteria) of Earth today, and they are orders of magnitude out of thermodynamic equilibrium with each other. This is the least ambiguous known way of detecting life remotely. Ozone (O_3) in large amounts is a secondary biomarker, since it is directly produced by the action of sunlight on O_2 . Thus, ozone is useful for indirectly assessing the oxygen content of an atmosphere.

Probable Evidence of Life

The presence of a large amount of O_2 , without a search for CH_4 or N_2O , would give probable evidence for life. This is because at present there are no known pathways for large amounts of O_2 to develop unless life is generating these molecules, although in the future such a process may be found.

The presence of a large amount of O_3 , without a search for O_2 , CH_4 , or N_2O , would also give probable evidence of life. This is because O_2 generates O_3 , as noted above, and O_2 by itself gives probable evidence. However some spectral features of O_3 are strongly saturated, so a measurement of the equivalent width of an O_3 feature only tells us that a certain minimum amount of O_3 is present.

The presence of the spectral signature of chlorophyll would also give probable evidence of life. However since the only known signature of chlorophyll is a broad enhancement of the reflectivity in a region of the spectrum, it is possible that rocks or clouds might mimic this signature, although at present there are no obvious candidates. Another caveat is that plants may have developed a different form of "chlorophyll" on another planet, and even different leaf cell structure, taking advantage of different chemical or radiative conditions than on Earth. At present we do not know what other possibilities exist for the formation of an alternative form of chlorophyll or leaf structure. Nevertheless, if we did measure a chlorophyll-like signature, we would need to seriously consider the likelihood of it being produced by green plants.

Input Ingredients of Life

A planet must be in the habitable zone of its parent star, and have an atmosphere that provides a surface temperature and pressure adequate to maintain liquid water at its surface. The water in cells must be liquid, so temperature is a critical parameter. However, even a planet whose *mean* temperature is too hot or too cold may have regions where liquid water and life exists. It is, therefore, important to provide sufficient spectral range and resolution to unambiguously detect atmospheric water vapor to distinguish a habitable planet from ones similar to Venus or Mars.

An atmosphere of CO_2 or N_2 may be a useful input ingredient for life, since it serves as a protective shield from high-energy stellar radiation and as a medium in which life may be fostered. A measurement of total atmospheric pressure would, therefore, be a useful indicator of a protective atmosphere.

H₂O and CO₂ are important indicators of the presence of an atmosphere and a possible hydrosphere, and they provide an important context for the interpretation of the significance of signatures such as O₂, O₃, or CH₄. Both CO₂ and H₂O are necessary for photosynthesis.

2.6 Characterization of Exozodiacal Dust Disks

Results from TPF should be capable of determining the spatial and mineralogical distribution of material in the zodiacal clouds of target systems. Determining and understanding the properties of the zodiacal cloud must be part of a comprehensive program of understanding the formation, evolution, and habitability of planetary systems. For example, how the quantity and composition of zodiacal material evolves with time may be due directly to the influx of solid and volatile material onto a forming Earth-like planet. The missions will have the sensitivity, angular resolution, and starlight suppression needed to further our understanding of solid material orbiting many target stars.

2.7 Other Astrophysics

The instruments that TPF will use for the detection of extrasolar planets could doubtless be used for a number of other interesting problems in astrophysics, and the TPF Science Working Group has been tasked with developing a white paper to address this subject. However, the astrophysical research that TPF could undertake is outside the scope of this document. The paramount scientific importance of TPF's primary goal in extrasolar planet research means that astrophysical considerations must be set aside in the development of the missions. The TPF observatories will be extreme technical challenges, so the use of TPF-C or TPF-I for astrophysics cannot be allowed to influence the design, performance, or cost of the missions in meeting their primary objective.

3 Characteristics of Extrasolar Planetary Systems

Relevance to TPF

The National Research Council decadal-survey report *Astronomy and Astrophysics in the New Millennium*, highlighted the importance of the frequency of Earths, η_{\oplus} , when it noted:

The committee's recommendation of this mission is predicated on the assumptions that TPF will revolutionize major areas of both planetary and nonplanetary science, and that, prior to the start of TPF, ground- and space-based searches will confirm the expectation that terrestrial planets are common around solar-type stars. NASA should pursue a vigorous program of technology to enable the construction of TPF to begin in this decade.

The TPF SWG and the Project recognize the importance of this recommendation both for giving NASA and the public the confidence to proceed with the development of TPF and to define key parameters of the missions. The Project believes that the best way forward is for TPF-C and TPF-I to be designed as capability-driven missions. The observatories must have an angular resolution and sensitivity capable of detecting and characterizing planets around a statistically significant number of stars. For example, this may mean having the ability to search all G type stars out to a distance of 15 pc. How many stars TPF-C and TPF-I will be capable of searching for planets, how large a volume of space they will search, will ultimately depend on the size of each observatory. The capability of the missions will therefore involve a trade between the expected science return and the technological challenges of building larger observatories. This chapter highlights the techniques that will in this decade advance our understanding of extrasolar planetary systems, build confidence in the mission design, and assist in defining the scope of TPF.

Metrics for Decision Making

Prior to the launch of TPF-C, advances in our knowledge of extrasolar planetary systems are most likely to come from radial velocity measurements, the results of the COROT (CNES) and Kepler (NASA) transit-survey missions, and from planet searches with the Space Interferometry Mission (NASA). As shown in Fig. 5, by 2010 our understanding of extrasolar planets should have advanced sufficiently to allow us to interpolate the distribution of planets across TPF's region of interest, and in so doing provide an improved estimate of the frequency of Earths.

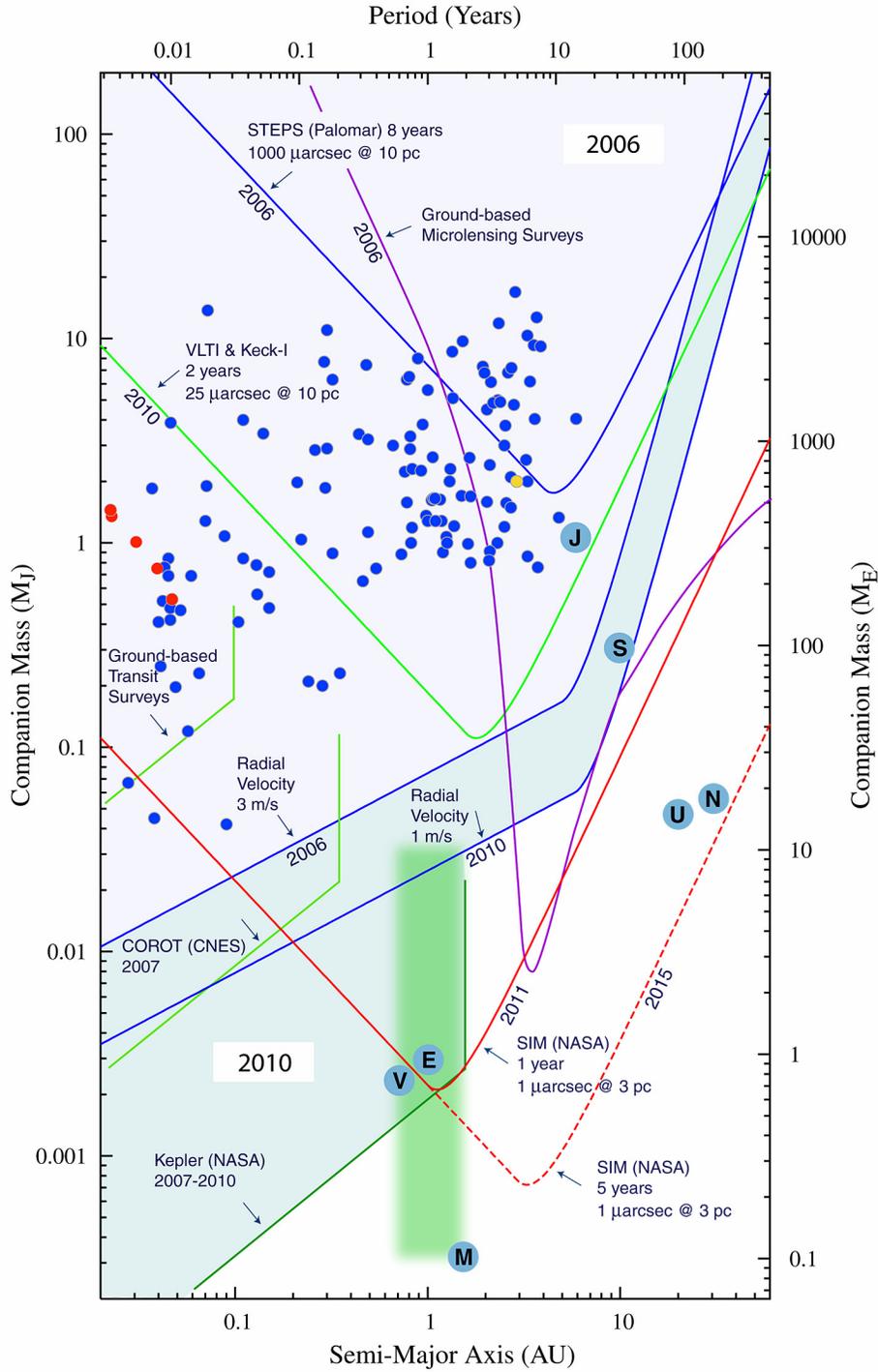


Figure 5. Limiting sensitivity of techniques of planet finding. Shown in the above figure are the sensitivity limits of radial velocity surveys, astrometric surveys, microlensing surveys, and space-based transit techniques. The lines show 5- σ limits with 50 re-samples. The shaded areas show the expected progress towards the detection of Earth-like planets by 2006 and 2010. Planets in our Solar System are also indicated, as well as the highlighted target area of TPF science. The filled circles indicate the planets found by radial velocity surveys (blue), transit surveys (red), and microlensing surveys (yellow). The discovered extrasolar planets shown in this plot represent the reported findings up until August 31, 2004.

More certain knowledge of the characteristics of extrasolar planetary systems will allow the TPF Project to determine the scope and science return of the mission prior to entering Phase B. In the latter phases of the project life-cycle, improvements in the statistics of extrasolar planets will allow a further refinement of the target list and improved scheduling of the mission timeline.

Schedule and Deliverables

Figure 5 shows the wide variety of ongoing or planned observational efforts relevant to studies of extrasolar planets, including the highly successful radial velocity surveys and planned experiments using astrometry, transits, and microlensing. These observational programs progress with time from 2004 up to around 2010 when Kepler will have obtained the first direct results on the incidence of Earth-sized planets in 1 AU orbits. SIM results will come late enough that they will be primarily of interest in characterizing and prioritizing potential TPF target stars rather than in setting the scope of the mission in advance of Phase B/C/D.

3.1 Radial Velocity Surveys

Current State of the Art

The spectroscopic measurements used in radial velocity surveys detect the reflex motion of the star in response to the orbiting planet, but because the inclination, i , of the planet's orbit is usually unknown, only a lower-limit to the mass is derived: $M \sin i$. Radial velocity precisions of 1–3 m/s have resulted in the detection of more than 120 gas giant planets orbiting nearby stars. Values of $M \sin i$ and the semi-major axes of the orbits of these planets are plotted in Fig. 5. Figure 6 shows a mass histogram of planets detected to date. Radial velocity detections require the observation of at least one full orbital period to characterize a planet. As a consequence, this technique first detects planets with short orbital periods. Indeed, most extrasolar planets with $M \sin i > 0.5 M_J$ and orbital periods less than 1 year have already been culled from the collective planet surveys of the brightest and closest 2500 stars. Reflecting the growing time baseline of radial velocity surveys, extrasolar planet detections since 2002 typically have orbital periods longer than two years. The statistics for stars that have been included in radial-velocity surveys for at least eight years show that:

- 1% of stars have gas giant planets with orbital periods less than 10 days (hot Jupiters).
- 15% of stars have detectable gas giant planets in orbits less than 10 years (that number is a lower limit and will continue to grow).
- More than half of stars with one detected planet show radial velocity variations indicating the presence of additional gas giant planets.
- The mass distribution increases toward the low $M \sin i$ detection threshold.
- A wide range of eccentricities is observed: hot Jupiters reside in nearly circular orbits because of tidal interactions; planets with orbital periods between 10 days and several years have $0 < e < 0.7$; and although the statistics are currently poor, the data suggests that gas giant planets with orbital periods of several years exhibit a lower range of eccentricities (between circular and $e \sim 0.1$ – 0.3).

There have been significant improvements in the past few years in both hardware and software development for échelle spectrometers that have led to radial velocity precisions of 1–3 m/s. With this precision, several Neptune-mass planets have now been detected in short-period orbits.

Expected Near-term Progress

In order to detect lower-mass or longer-period planets and the intricate details of multiple-planet orbits, radial velocity precision and survey time duration must improve. As radial velocity precision improves, astrophysical contributions to radial velocities will become important for many (perhaps most) stars. The improved precision, combined with high cadence observations will result in the detections of planets with $M \sin i$ less than Neptune masses and with orbits up to approximately 1 year. Work in this area is just beginning and should reach fruition over the next 5–10 years. Table 2 (page 24) lists some of the surveys that are ongoing. Other spectrometer designs (e.g., dispersed interferometers) have the potential for comparable performance, and perhaps higher efficiency. Observational programs are now starting and will test the performance and long-term stability of these designs.

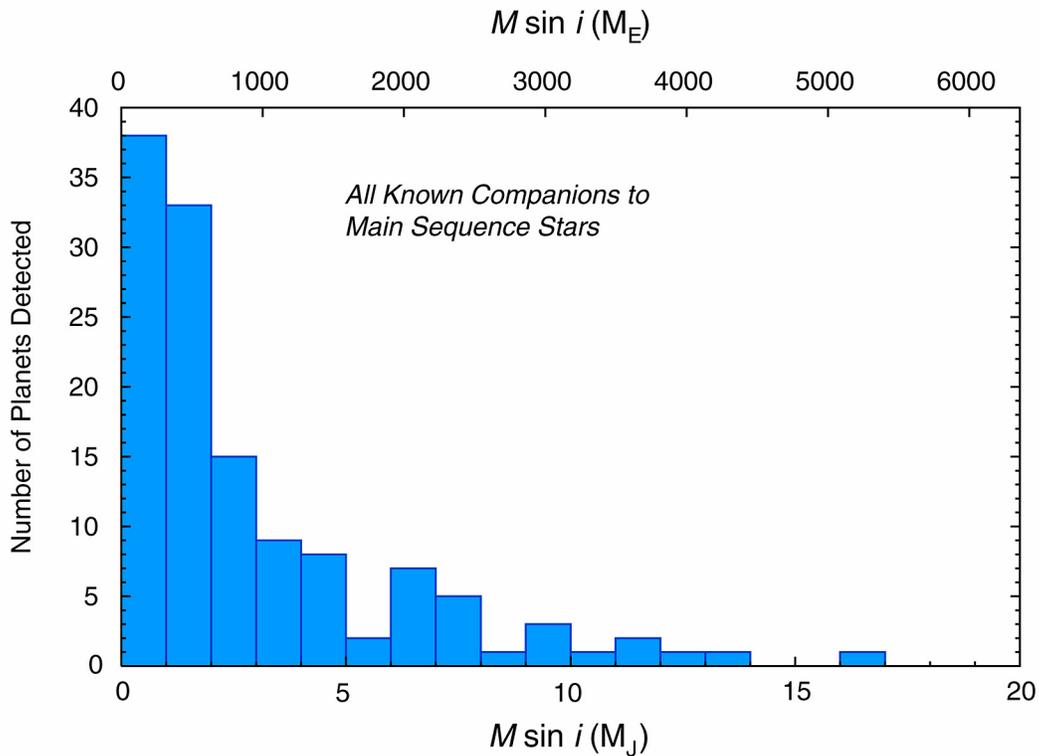


Figure 6. Mass histogram of extrasolar planets detected by radial-velocity surveys. The rising mass-distribution of planets less than 5 Jupiter masses shows that lower-mass planets are more common than more massive ones. The data represent the 127 planets reported as of August 31, 2004.

Table 2. Planet Searches Using Radial Velocity Measurements

Collaboration	Telescope	Instrument	Stars	Sensitivity	Timeline
California & Carnegie Planet Search	WMKO, 10-m	HIRES	900	3 m/s	1996–2003
	WMKO, 10-m	HIRES Upgrade	1000	1 m/s	2004–onwards
	Lick Obs., 3-m	Hamilton	300	5 m/s	1992–onwards
Anglo-Australian Planet Search	AAT, 3.9-m	UCLES	150	3 m/s	1998–onwards
Geneva Planet Search	OHP, 1.93-m	Elodie	320	8–12 m/s	1994–onwards
	ESO, La Silla 1.2-m	Coralie	120	3–6 m/s	1998–2003
	ESO, La Silla 3.6-m	HARPS	1000	1 m/s	2003–onwards
Kompetenzzentrum fuer Exo-planeten, Jena/Tautenburg	VLT, 8.2-m	UVES		6 m/s	2001–onwards

Contributions to TPF Precursor Science

Radial velocity measurements have already determined that the frequency of gas giant planets in the habitable zones — detrimental to the existence of habitable terrestrial planets — lies between 10 and 15%. Within the next five years, radial velocity measurements will push to lower mass limits ($\leq 14 M_{\oplus}$) and longer period planets (> 15 years). The information on longer periods is particularly important in defining Solar System analogs with massive planets (if any) outside the habitable zone. The statistics of known planetary systems with giant planets similar to our own will provide a lower limit to the number of habitable planets we should expect to find.

3.2 Transit Surveys

Current State of the Art

Observations of both photometric transits and radial velocity variations will play an important role in our understanding of extrasolar planets, for much the same reasons that eclipsing binaries are central to our understanding of stellar physics. If both observations are possible with individual planets, it becomes possible to estimate directly the planetary mass and radius, hence density, and by inference, composition. Moreover, through the technique of transmission spectroscopy, transiting planets allow us a glimpse at the component we most desire to study, namely the atmosphere. The planet HD 209458b, whose transit is plotted in Fig. 7, exemplifies the dramatic impact of transiting planets on the field; the radius and mass of this planet are known with excellent precision, and both sodium and hydrogen absorption features have already been detected in its atmosphere. These detections were made by the Hubble Space Telescope, following up on the initial ground-based photometric detection.

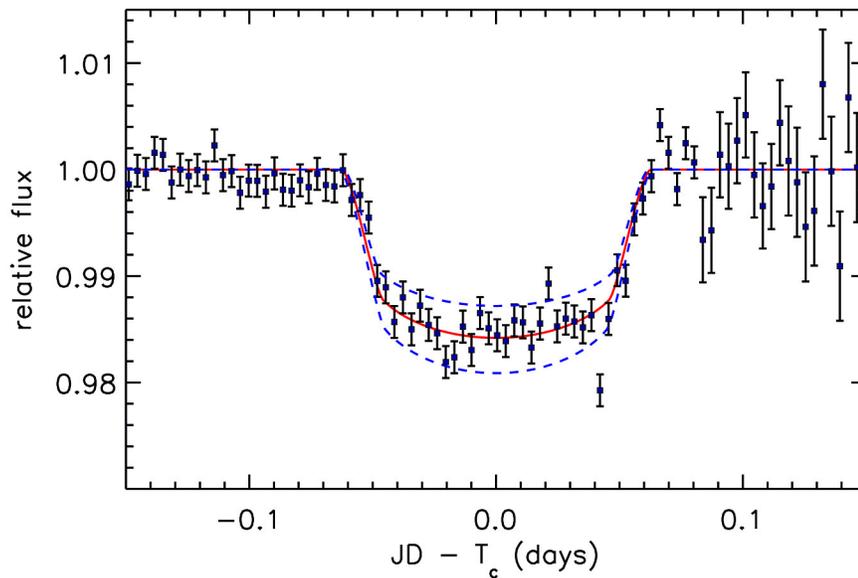


Figure 7. Light curve for the transit of HD 209458. The solid line is the transit shape that would occur for the best-fit model. The lower and upper dashed lines are the transit curves for planets 10% larger and smaller in radius, respectively.

To date, five more transiting planets have since been discovered: OGLE-TR-56b, OGLE-TR-113b, OGLE-TR-132b, OGLE-TR-111b, and TrES-1. The current status of this method is analogous to that of the radial velocity technique prior to 1995. There are now tantalizing results, but the best procedure has not yet been identified. Moreover, ground-based transit searches are impacted by incomplete sampling due to weather, diurnal changes, and seasonal effects, as well as to confusion with eclipsing binary systems. Procedures need to be further developed that allow for an efficient rejection of false positives.

Expected Near-term Progress

More than 20 photometric surveys for transiting extrasolar planets are currently active. Table 3 (page 26) lists several ground-based surveys currently operating. In the next few years, these surveys will likely detect roughly a dozen gas giant planets in short-period orbits (while terrestrial objects will remain well beyond the reach of these ground-based instruments). These surveys differ primarily in the typical brightness of the target stars. Many small-aperture, semi-robotic, dedicated wide-field transit surveys are now operational. These projects will likely yield the greatest scientific impact for two reasons. First, the target stars are sufficiently bright to permit an accurate determination of the star's radial velocity (and thus the planet's mass), to enable numerous follow-up studies of the planet's atmosphere and to foster a search for additional bodies in the detected planetary systems through high-precision photometry and timing measurements. Second, transit searches typically require a long observing campaign to detect multiple transit events, and most shared facilities are hard-pressed to accept this burden of telescope time.

Table 3. Ground-based Transit Surveys to Detect Earth-Like Planets

Program	Telescope	Stars	Sensitivity	Timeline
Arizona Search for Planets (ASP)	Kitt Peak, 0.9-m	5,600 & 11,500	2.4×10^{-4} magnitudes	1996– onwards
Berlin Exoplanet Search Telescope (BEST)	Thueringer Landessternwarte, Germany, 20 cm	30,000	$< 1 \times 10^{-2}$ magnitudes	2001– onwards
Trans-Atlantic Exoplanet Survey (TrES)	STARE, Tenerife, Canary Islands, 10 cm; PSST, Lowell Obs.; Sleuth, Palomar Obs.	24,000	1.5×10^{-3} magnitudes	1999– onwards
Survey for Transiting Extrasolar Planets in Stellar Systems (STEPSS)	Kitt Peak, 2.4-m	NGC 1245, NGC 2099	$< 1 \times 10^{-2}$ magnitudes	2001– onwards
Tennessee Automatic Photoelectric Telescope	Tennessee State University, Smithsonian Astrophys. Obs., 0.8-m	75 solar-type stars	$1-2 \times 10^{-4}$ magnitudes	1996– onwards
Transits of Extrasolar Planets (TEP) Network	Telescopes at IAC, OHP, JKT, INT, Lick Obs., Wise Obs., and others	CM Dra	$2-3 \times 10^{-3}$ magnitudes	1994–2001
Vulcan Camera Project	Mt. Hamilton, California, 5.4 cm	6000	1×10^{-2} magnitudes	1999– onwards

Table 4. Space-based Transit Surveys to Detect Earth-like Planets

Program	Description	Stars	Sensitivity	Timeline
MOST (CSA)	Detection and characterization of reflected light from known hot giant extrasolar planets, to determine sizes and atmospheric compositions.	51 Peg, ϵ Eri, HD 38529, τ Boo, HD 209458	1.0×10^{-6} magnitudes	2003–2005
COROT (CNES)	Capable of detecting a $2 R_{\oplus}$ planet in a 0.2 AU orbit around 11–15.5 mag star in 1 hr.	30,000 stars	$0.7-5.0 \times 10^{-3}$ magnitudes	2006–2009
Kepler (NASA)	Capable of detecting a $1 R_{\oplus}$ planet in a 1 AU orbit around a 12 magnitude star in 6.5 hrs.	100,000 stars	$< 1.0 \times 10^{-5}$ magnitudes	2007–2012

Contributions to TPF Precursor Science

Within the next 4 years (2004–2008), the Canadian Space Agency's MOST project and the CNES's COROT project offer the prospect of finding planets of a few Earth radii in short-period orbits through precision transit photometry. Space-based transit missions are listed in Table 4. An observational knowledge of the frequency of Earth-sized objects even in such short orbits, combined with a comprehensive theoretical framework, will nonetheless improve the estimate of η_{\oplus} . On the slightly longer term (beginning in 2007), Kepler will extend COROT results to smaller sized planets in orbits within a few tenths of an AU and by 2010 will have directly measured statistics of Earth-like planets in the habitable zone.

3.3 Microlensing Surveys

The detection of gravitational microlensing events will also play a role in the discovery of extrasolar planets. Lensing events occur when a foreground object passes through the line-of-sight between a star and the Earth, producing a characteristic broad light curve, which may last several weeks. If the foreground object is a star with a planetary system, the broad light curve may include brief spikes in brightness that mark the passage of planets. Because these events are so rare, the observing strategy is to monitor large numbers of stars in regions of sky in the direction of the Galactic bulge, or parts of the Magellanic clouds. The first planet detected by this method is illustrated in Fig. 8, inferred to be a 1.5 Jupiter-mass planet in an orbit of ~ 3 AU.

Microlensing is most sensitive to planets at a projected distance from the lensing star of about an Einstein radius. In practice, it should be capable of detecting M_J companions between 1–10 AU. The duration of the planetary perturbation on the light curve is proportional to the square root of the planetary mass.

Current State of the Art

Several microlensing surveys have been ongoing since the early 1990s. Details of selected programs and follow-up planet searches are given in Table 5 (page 28). Up until 2003 there had been no firm detections of planets, and the detection of OGLE 2003-BLG-235 provided a solid demonstration of the technique. There are two major surveys, OGLE and MOA, and two follow-up programs the Microlensing Planet Search (MPS) and the Probing Lensing Anomalies NETWORK. The PLANET network had reported that an analysis of 43 microlensing events from 5 years of survey work revealed no indication of anomalies that would indicate the presence of planets. The lack of any detected planetary signature implied that less than 1/3 of M-dwarfs have Jupiter-mass companions orbiting at 1.5 to 4 AU. Analysis of 3 years of OGLE observations from 1998 to 2000 likewise placed limits on the abundance of Jupiter-mass planets at distances of ~ 1 to 4 AU from their host stars: of 145 events, two detections were plausible candidates, suggesting that no more than 14 % of the lens stars have Jupiter-mass planets in such orbits.

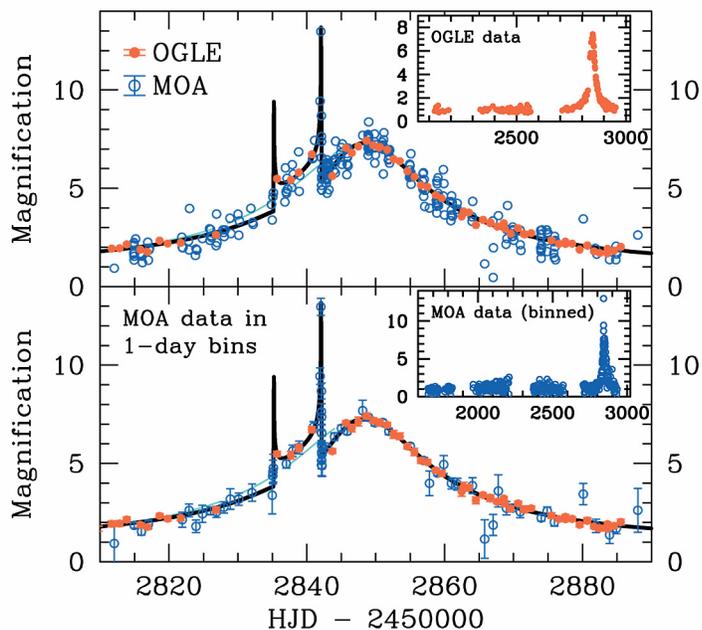


Figure 8. Light curves with best-fit models of the binary microlensing event OGLE 2003-BLG-235/MOA 2003-BLG-53. OGLE and MOA measurements are shown as red filled circles and blue open circles respectively. The bottom panel is the same as the top panel, but with MOA data grouped in 1-day bins. The inferred secondary object is a planet of about 1.5 Jupiter masses with an orbit of ~ 3 AU.

Expected Near-term Progress

The detection probability of terrestrial planets is a small fraction of that of the gaseous giant planets. More timely and complete ground-based coverage of lensing events may be capable of detecting planets with several Earth masses in orbits of 2–6 AU.

Contributions to TPF Precursor Science

Microensing is currently the only ground-based technique with the ability to detect planets of several Earth masses in orbits of several AU around main-sequence stars. Ground-based microensing surveys could provide the first few detections of such planets and contribute to our knowledge of η_{\oplus} . A space-based microensing mission would be sensitive to Earth-mass planets in the habitable zone, and if implemented before the launch of TPF-C, would help further refine our knowledge of η_{\oplus} .

Table 5. Ground-based Microensing Surveys

Programs	Telescope	Target Field	Status
EROS I and II	La Silla Obs. (ESO): 40-cm, and 1.5-m Marly Telescope	Galactic Bulge	1990–1995 1996–2003
MACHO	Mt. Stromlo Obs., 50-inch telescope	Galactic Bulge, Large Magellanic Cloud	1992–2003
MOA	Mt. John Univ. Obs. (New Zealand), 61-cm telescope	Galactic Bulge	1999–onwards
OGLE I, II, and III	Las Campanas Obs. 1.0-m Swope, and 1.3-m Warsaw Telescopes	Galactic Bulge	1992–1995 1997–2000 2001–onwards
Microensing Planet Search (MPS)	Mt. Stromlo Obs., 1.9-m telescope; Boyden Obs. 1.5-m telescope	Follow-up planet search to MACHO, OGLE, and EROS microensing alerts	1997–onwards
PLANET Network	La Silla Obs 0.91-m, South African Astron. Obs. 1-m, Perth 0.6-m, and Hobart 1-m telescopes.	Follow-up planet search to MACHO, OGLE, and EROS microensing alerts	1995–onwards

3.4 High-contrast Imaging

Current State of the Art

High-contrast imaging is currently practiced through direct imaging and coronagraphy with various HST instruments and adaptive optics coronagraphy on large ground-based telescopes. Nearby star companion searches have been carried out by many groups, but with few results. Current and future imaging work is listed in Table 6. For both ground and space techniques, the demonstrated performance limits are point source detections at contrasts of ~ 10 mag at $r = 0.5$ arcsec. The key factor limiting performance is

uncorrected wavefront errors due to the atmosphere or imperfect optics. Precision deformable mirrors with larger formats, improved wavefront sensors, and data analysis techniques to enable accurate subtraction of the residual stellar halo will be essential to overcoming this limitation, both on the ground and in space.

Expected Near-term Progress

Direct detection of young (≤ 1 Gyr) or massive ($> 10 M_J$) brown dwarf companions at orbital separations > 5 AU can be expected with improved high-contrast adaptive optics instrumentation on ground-based telescopes. A separate but related avenue of work is near-IR interferometry on large ground-based telescopes, which should directly detect and characterize hot gas giants that are known around ~ 20 nearby stars. The HST experience has shown that space-based coronagraphy can exploit the stability of the instrumental point spread function. Several space-based precursors to TPF-C have been proposed to exploit this PSF stability advantage, and make use of optimized coronagraphs with adaptive optics to further suppress the PSF within $3''$ of the star.

Contributions to TPF Precursor Science

Ground-based AO coronagraphs and interferometers using existing telescopes represent relatively modest investments that could return exciting scientific results on young or massive giant planets. A decade from now, new 30-m class ground-based telescopes, if equipped with high performance AO systems, could begin direct detections of mature jovian planets in reflected light. Furthermore, if a 2-m class space-based optical coronagraph were supported, for example through a NASA Discovery mission, it could provide the first census of jovian planets in the outer (> 5 AU) region of nearby stars, complementing the reflex motion planet searches, and giving us a better idea of the frequency and diversity of planetary systems. Such a mission could also image hundreds of debris disks down to 10 zodi optical depths, resolving resonant

Table 6. Ground-based and Space-based High-Contrast Imaging

Ground-Based Programs	Target Sample	Timetable
AO on large telescopes	$> 10 M_J$, 1 Gyr objects @10 pc	Ongoing
Differential phase interferometry	~ 20 hot gas giants	2005–onwards
Keck/LBT nulling interferometry	~ 20 hot gas giants	2005/2006–onwards
Extreme AO on future large telescopes	$> 1 M_J$, 5 Gyr planets $d < 20$ pc	2012–onwards
Space-Based Programs	Target Sample	Timetable
HST coronagraphy	Nearby M/L dwarfs	Ongoing
Spitzer/IRAC	Nearby M stars, $a > 50$ AU	2003–2008
2-m class coronagraph	$1 M_J$, 5 Gyr planets in 100 A, F, G, K stars	2010*
JWST/NearCAM	$1 M_J$, 5 Gyr planets at late M stars	2012–onwards

*Prospective Discovery-class mission

structures that might indirectly indicate the presence of planets. JWST, while not an optimized high contrast imager, may be able to detect mature ($1 M_J$, 5 Gyr) jovian companions to nearby late M stars, search for luminous extrasolar planets in young stars, and study the chemical evolution of circumstellar disk material.

3.5 Precision Astrometry

Current State of the Art

The current state of the art in ground-based CCD astrometry is defined by results from 4–5-m class telescopes. The astrometric signal amplitude from a Jupiter-mass planet around a solar-type star at 10 pc is ~ 0.5 mas. Several astrometric programs at meter-class telescopes have obtained ~ 1 mas accuracy in proper motion and parallax estimation, but they have not achieved the performance required to detect extrasolar planet signals with unknown orbital parameters. Long term stability of < 1 mas has been demonstrated in a program that observes nearby M-dwarfs. M-dwarfs were selected because they are low-mass and faint, enhancing the signal and permitting nearby faint reference stars.

The current state-of-the-art in small-field space-based astrometry is defined by measurements made with Fine Guidance Sensor 3 of the Hubble Space Telescope, capable of a small-field astrometric precision of 1 mas. Targeted measurements of Proxima Centauri and Barnard's star provided companion mass detection limits of $1 M_J$ for orbits with semi-major axes of 0.1–1.0 AU.

Expected Near-term Progress

Improved astrometric measurements using single ground-based telescopes are possible with the use of larger apertures. Larger apertures provide improved averaging of turbulent atmospheric layers. Their greater light-collecting power allows a smaller field-of-view and narrower bandpass for detecting stars that define a reference frame. The turbulence-averaging and smaller field-of-view combine to reduce the relative motion of the target and reference stars, while the reduced bandpass improves differential chromatic refraction, the major systematic error. The observing time to achieve an astrometric noise level can easily be an order of magnitude smaller for a 5-m telescope than a 1.5-m telescope at the same site.

Over the next few years, astrometry with ground-based infrared interferometers should permit an order of magnitude improvement in ground-based, narrow angle astrometric measurements with a precision approaching $20 \mu\text{as}$. In 1999 the Palomar Testbed Interferometer, located at a site with only modest seeing conditions, demonstrated that a precision of $\sim 30 \mu\text{as}/\text{hr}^{1/2}$ was possible using this technique. As shown in Table 7, newly developed astrometric interferometers, located at world-class observing sites, are expected to be operational within five years. The expected precision of $20 \mu\text{as}$ will then allow measurements of planets with masses comparable to Jupiter, Saturn, or Uranus in orbits that are Jupiter-like out to a distance of about 20 pcs.

Table 7. Ground and Space-Based Astrometric Planet Searches

Ground-Based Astrometry	Mass Limit	Timeline
Single-telescope astrometry	320 M_{\oplus} (1 M_J), 1000 μas at 10 pc	Ongoing
Keck-Interferometer	20 M_{\oplus} @ 5 AU (25 μas at 25 pc)	2008–2013
VLTI (ESO)	25 M_{\oplus} @ 1 AU, 10 μas at 10 pc	2006–2012
Space-Based Astrometry		
Hubble Space Telescope / FGS	320 M_{\oplus} (1 M_J) @ 1–2 pc	1992–1999
SIM (NASA)	3 M_{\oplus} @ 3–10 pc	2010–2020

Interferometry from space will revolutionize the entire field of precision astrometry. Currently scheduled for launch in early 2010, the Space Interferometry Mission (SIM) will have a precision of 1 μas in a single measurement, almost a factor of 1000 better than currently available from the ground or with HST. As a pointed instrument, it will be able to observe much fainter targets than ground-based interferometers, which are expected to reach about 20 μas precision.

Contributions to TPF Precursor Science

The astrometric approach to planet detection is complementary to the radial-velocity technique. Whereas radial velocity surveys are most sensitive to massive planets with close-in orbits (causing detectable radial-velocity shifts), astrometric surveys are more sensitive to planets with wider orbits (providing a measurable astrometric signal) and also have a lower detectable mass-limit. In this way, astrometric surveys may be better suited in the long-term to detecting planetary systems similar to our own.

In the context of TPF, ground-based astrometric interferometers, such as Keck-I and VLTI, are important for detecting and determining the masses of long period gas-giant planets around TPF targets. Only such facilities can produce the long time baseline of observations needed to determine orbits at or beyond the distance of Saturn with its 30-year period.

SIM is one of the most important precursor missions for TPF. It will explore the scientific landscape for TPF in several ways.

1. *SIM will provide a complete survey of all likely TPF targets:* SIM has three approved key projects to perform astrometric searches for planets around nearby stars. The SIM target list will be a super-set of the entire TPF list. The scientific implication is profound: for every TPF target, we will know what planetary-mass bodies each system contains, for periods less than about 10 years and masses down to a few Earth masses. Radial velocity measurements are complementary to SIM: for long-period planets, SIM fills in the search space for which radial velocity measurements are unable to detect even Jupiter-size planets.
2. *SIM will measure planet masses:* Except for microlensing events (which are one-time snapshots of very distant stars, none of which can be TPF targets) only SIM measures mass directly. Mass is the

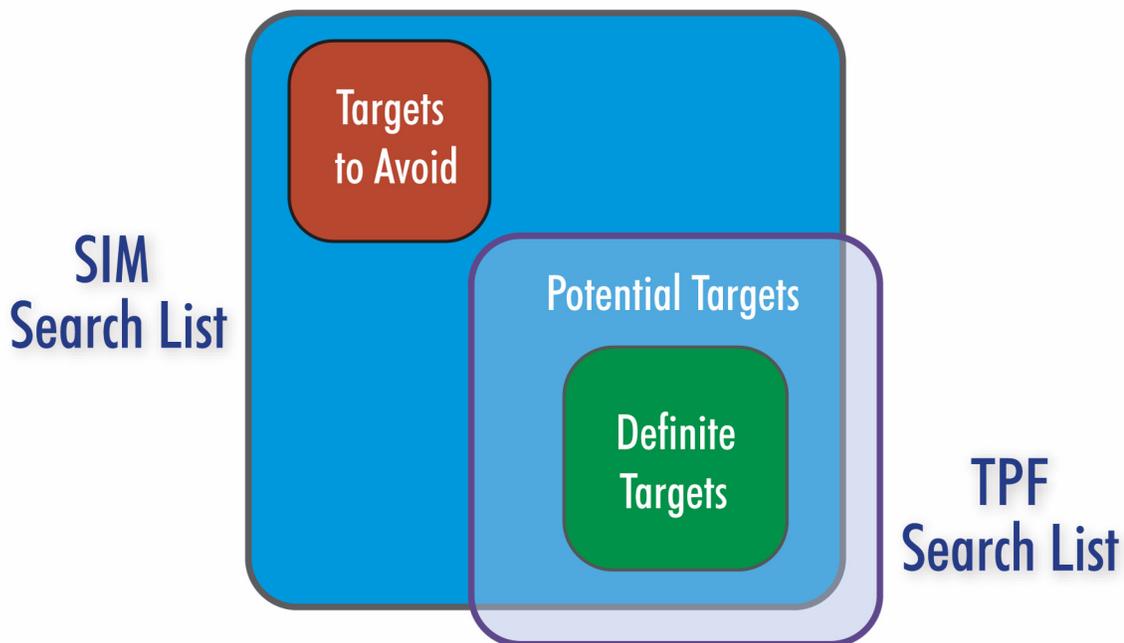


Figure 9. Venn diagram showing the relationship between SIM search lists and TPF target lists. Observations with SIM will contribute to refining the target lists for both TPF-C and TPF-I. Results from SIM will help prioritize the TPF target lists and identify targets to be avoided.

most fundamental property of astronomical body. Knowing the masses of planets, when found, in systems around TPF targets is vital information to understanding the significance and the context of any TPF-detected terrestrial planets. Mass is the single most important parameter that TPF will not measure. With sufficient SNR in the planet spectrum, the mass of a planet can be inferred indirectly from modeling the atmosphere as a function of surface gravity. But the model parameter space is large (in some cases, mass derivations are double-valued), and we have only our own solar system bodies for reference, so making a definitive claim for an Earth-like planet is greatly strengthened by knowing the mass.

3. *SIM will measure all orbital elements:* Radial-velocity measurements cannot detect whether multiple-planet systems are co-planar, which is essential to understand the stability of planets in the habitable zone. The fact that most radial-velocity detected planets are in very eccentric orbits strongly suggests that co-planarity is an important open issue to be studied.
4. *SIM will screen the TPF target list:* Since SIM will be capable of detecting planets in the range of mass and orbit radius of interest to TPF, it can serve to identify good and bad targets — or at least assist in the priority order for observation, as illustrated in Fig. 9. SIM will identify the targets to avoid, for example systems where there are one or more giant planets in the habitable zone. It will also identify high-priority targets, those for which terrestrial planets have already been detected. If such planets are common, then SIM should detect at least a few which also lie in the habitable zone around their parent stars. There will also be potential targets — those in which SIM finds either no planets at all, or massive planets in orbits which permit stable orbits in the habitable zone. For our

Solar System, this would be equivalent to detecting Jupiter and Saturn, then (correctly) inferring that the Sun is a good target star for a terrestrial planet search.

5. *TPF will mine the SIM data archive:* SIM will likely yield several marginal detections for every positive detection. A joint solution for orbital elements using SIM and TPF data would allow masses and orbits to be derived for many more planets; roughly a factor of two improvement in the SIM mass limit can be expected.

If complex planetary systems prove to be the norm, then it will be more challenging for SIM to determine the orbits for planets within each system. However, an extended mission of up to 10 years and monitoring by ground-based astrometric interferometers over longer periods should resolve ambiguities in the data.

3.6 Theory and Modeling of Extrasolar Planetary Systems

A quantitative and testable theory of planet formation is the essential conceptual basis of searches for extrasolar planets. Considerable new insights in planetary formation within protostellar disks have been gained in the past few years as the discovery of extrasolar planets has widened our horizon. New theoretical models will allow us to predict and to confront the observable statistical properties of newly found extrasolar planets and the diversity of planetary systems. For the TPF precursor science program, a concerted theoretical program to understand the detailed process of planetary formation is particularly relevant to paving the path for TPF's central mission.

3.6.1 Protostellar Disk Formation

Today, the most basic construct of planet-formation theories remains similar to Laplace's nebula hypothesis in which planets and their host stars are assumed to form concurrently, with the former in gaseous disks surrounding the latter. New quantitative models of the solar nebula and rigorous theories of accretion disks have been developed recently to study the structure, stability, and evolution of protostellar disks. However, there are numerous paradoxes in the current theoretical models that must be resolved before a comprehensive and deterministic theory of planet formation can be constructed that is both compatible with the most crucial existing observations and has predictive powers to guide future missions.

Current theoretical studies of the structure and evolution of protostellar disks need to be continued and expanded so that the physical conditions and the persistent time scale of nascent disks can be more accurately defined. Theoretical investigations are needed to identify the processes that determine the retention efficiency of heavy elements in planets, formation probability of planets, and growth time scale of planetesimals. Special efforts should be made to identify observable signatures of planetesimals' growth in their nascent disk environment. Concurrent observations of the dust-and-gas phase transition, the grain-size distribution, the evolution of protostellar and debris disks, and the metallicity of their host stars will be mutually beneficial and fruitful. Theoretical efforts toward improving our knowledge of protostellar disk models should provide a variety of plausible boundary conditions to delineate the time-scale, efficiency, and outcome of planet formation.

3.6.2 Planetesimal Formation

A necessary step in the formation of terrestrial planets is the formation of planetesimals. At present, very little is known of how they form, under what conditions, and with what efficiency. Does metallicity need to be high? Do chondrules need to form first? What range of nebula turbulence is compatible with forming planetesimals? Further research is needed to be able to predict with what frequency planetesimals are formed from circumstellar disks, and this in turn will set an upper limit on the frequency of Earths. Knowing the efficiency of conversion of dust to planetesimals helps to establish whether a system contains Neptune-like planets at 1 AU, Earth-like planets, or Moon-sized objects.

3.6.3 Asteroid Belt Formation

Asteroids are a promising source of volatiles for terrestrial planets, and their frequency has important consequences to the formation of atmospheres and hydrospheres, and therefore to planetary characterization. Theoretical work is needed to predict the formation of asteroids and asteroid belts which likely may occur in planetary systems. What determines whether planetesimals lead to terrestrial planets or asteroids? Where in the disk will each class of object form? If the habitable zones of most stars contain asteroids rather than planets, then Earth-like planets may be rare amongst our nearest stars.

3.6.4 Planet Formation

Generalizations of the theories of planet building are needed in order to assess the formation probability of individual terrestrial planets around stars with different masses, progenitor clouds, protostellar disks, metallicities, and formation environments (such as O-B associations or clusters). Preserved crater scars on Mercury, the Moon, and asteroids are unequivocal signs that they were formed through cohesive collisions of smaller building blocks. Despite this conceptual simplicity, the details of the growth from dust to planetesimals, protoplanetary embryos, and cores are not yet well understood. Most of the current theories and models of terrestrial planet formation are still based on the dynamics and meteoritic data of our own Solar System.

Improved computer simulations and statistical modeling of planetary growth are needed over a wide spatial and temporal range to understand the processes that determine the magnitude of the dynamical filling factors of planetary systems. Examples of previous work are shown in Fig. 10. The dynamical filling factor of the planetary embryos and residual protoplanets determines the capacity of any planetary system to bear Earth-size habitable planets. This factor regulates not only the planets' collision and growth rates, but also their orbital stability and evolution. These investigations are necessary for establishing the circumstances (e.g., orderly versus runaway coagulation) that may produce planetary systems with high dynamical filling factors, as well as those (e.g., grain depletion and strong perturbation) that may quench terrestrial-planet formation and lead to dynamically sparse planetary systems. Theoretical investigation is also needed to identify the determining factors in the difference in the mass of the atmospheres of terrestrial and giant planets.

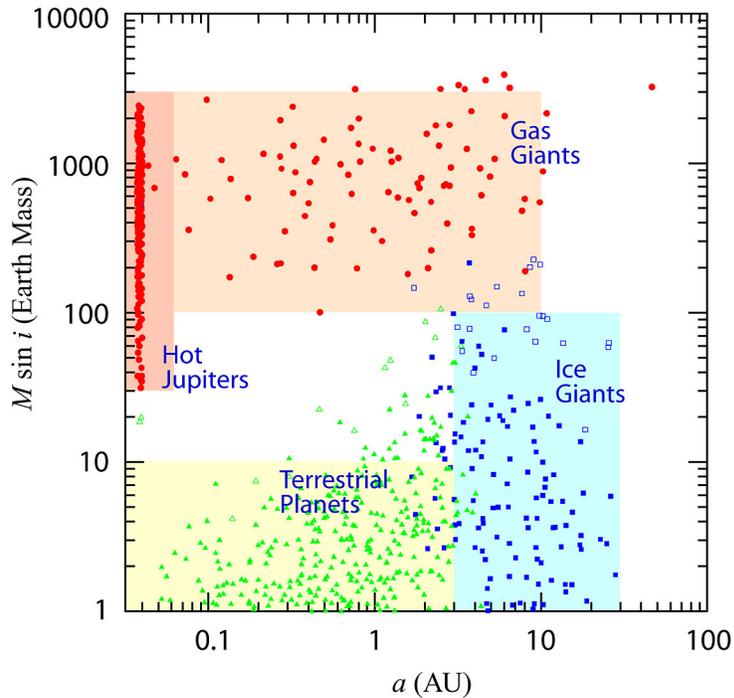


Figure 10. Results of simulations of 3000 planets evolved from simulated initial protoplanetary disks. The various types of resulting planets are highlighted. The blue and green *filled* shapes denote planets whose gas mass is less than its solid mass. The *open* blue squares and green triangles denote planets whose gas mass is less than 10 times their solid core mass. The filled red circles denote planets whose gas mass is greater than 10 times their solid core mass.

3.6.5 Giant Planet Formation

If, as core-accretion models would suggest, the formation of giant planets and planetesimals is associated, then observations tell us that planetesimals form around at least 10–15% of stars. Do giant planets form independently or in conjunction with terrestrial planets? How often? In what part of the disk? What are the timescales for formation? If giants tend to form on highly eccentric orbits, or within about 3 AU, or in multiple-planet systems with anything but low eccentricities, then terrestrial planets may not form due to giant-planet perturbations. The nature of giant-planet formation will strongly affect the delivery of volatiles to terrestrial planets.

It is important to carry out numerical simulations of various physical processes that determined the mass-distribution and orbital properties of Jupiter-mass planets. The two main classes of theories suggest that giant planets are either formed through 1) sequential core accretion or 2) gravitational instability. Although both models have their validities and represent circumstances that might occur in nature, we need to access their actual probability and to work out their implications:

1. The sequential-growth scenario requires the formation of terrestrial-planet-size cores prior to their gas accretion such that the coexistence of terrestrial and gas giant planets is naturally assumed. However, core accretion theories have been plagued by a growth-barrier and formation-time-scale paradoxes.
2. It is still unclear whether gravitational instability gives rise to planet formation, or instead simply results in changes in the structure of the disk.

Further theoretical analyses are needed to determine, under various possible conditions, the evolution of the rocky cores thought to exist within Jupiter, Saturn, and Uranus. The presence of such cores is generally interpreted as evidence for the emergence of terrestrial planets. The inference from the giant planets' structure to the potential coexistence of terrestrial planets needs a better theoretical understanding of the growth and survival of cores due to gas accretion, rapid envelope rotation, giant impacts, and intense tidal heating.

3.6.6 Orbital Stability

Theoretical investigation is needed to assess the persistence of terrestrial planets and to determine the range of survivable dynamical filling-factors in habitable zones. During post-formation evolution, secular perturbation between planets can strongly alter their initial kinematic properties. Under their mutual secular perturbation, terrestrial planet properties such as semi-major axis, eccentricity, and obliquity may evolve. This evolution process may become more active in systems with larger dynamical filling factors. The application of secular perturbation is directly relevant for the determination of possible eccentricity, inclination, stability, and survivability of terrestrial planets in habitable zones around host stars with previously discovered gaseous giant planets. Orbital modulations may be important for the emergence of life on these planets. It may be true that terrestrial planets are rare among the stars with known Jupiter-mass giant planets: celestial mechanics of the Solar System indicates that the orbits of terrestrial planets may be strongly perturbed by their secular interaction with the more massive giant planets, and many extrasolar planets have larger mass, greater eccentricity, and smaller semi-major axes than Jupiter. Secular perturbations induced by them are likely to be more intense.

Theoretical models are essential for the assessment of the orbital stability and evolution of multiple-planet systems. These calculations include the perturbation of the terrestrial planets on the orbit of gas-giant planets. Self-consistent models are needed to establish the orbital configurations of mutually interacting planets around common host stars. In the current search for terrestrial planets, numerical computation is essential for extracting dynamical information from radial-velocity and astrometry data.

3.6.7 Planetary Migration

The discovery of extrasolar giant planets in orbits close-in to their parent stars has forced a major revision of theories of planet formation. Since it seems unlikely that gas giants could form close to their parent stars, they are thought to have formed at much greater distances and then migrated to their present orbits.

In type I migration, the planet does not clear a gap in the disk from which it forms, but changes its orbit due to the torques generated by the wakes it creates in the surrounding disk. In type II migration, a newly formed large planet opens a gap in the circumstellar disk and subsequently evolves with it. The statistics of

planetary migration have important consequences for the frequency of Earths. As giant planets migrate, so do their unstable resonances, and resonance sweeping may remove terrestrial planets from many systems in which they form. If gas giants commonly migrate through the terrestrial region in the disk lifetime, terrestrial planets may rarely form. Under what conditions are type I and type II migration effective? What are the migration timescales? At what stage in the disk lifetime can this occur?

It will be useful to identify the effect of gas-giant planets' orbital migration and eccentricity excitation on the emergence of terrestrial planets in habitable zones. Orbital migrations can lead to resonant capture, divergent orbital evolution, and dynamical instability among some known multiple gas giant planetary systems. The extension of these theoretical studies to terrestrial planets will determine their post-formation migration, depletion, and resurgence in the habitable zone. An extrapolation of the migration theory and inference on the possible existence of hot Earth, in systems with or without hot gas giants, will help to establish the terrestrial-planet-formation efficiency with transit searches.

Theoretical analyses are needed to understand the effects of dynamical perturbation by either emerging or pre-existing giant planets on the formation environment, process, and orbital stability of terrestrial planets. A related issue is whether the spatial segregation of terrestrial and giant planets is universal or unique to the Solar System. Theoretical investigation is also needed to identify if the formation of one giant planet may promote and enhance the subsequent formation of other giant planets, as perhaps indicated by radial-velocity surveys. It will be important to understand as well if the emergence of Jupiter may have suppressed the formation of modest-sized, let alone giant planets, in the region of the asteroid belt.

3.6.8 From Gas Giants to Earth-Like Planets

Theoretical predictions of the frequency of Earths are tied to the mechanism by which terrestrial planet formation is modeled. For example, models based on core accretion should predict that Earths are common and may be found around the same host stars where Jupiter-like gas giants have been detected. It is, therefore, important to determine the dominant mechanism of terrestrial planet formation.

Once the dominant formation mechanism has been identified, we can apply theoretical models to analyze the observed properties of gas giant planets and extrapolate the efficiency of Earth formation. Projecting from the success of the past eight years, we can anticipate the discovery of a large number of new planets from which to base our predictions. This new data will provide input to theoretical models with which we can extrapolate the production rate of Earths. For stars with no known gas giant planets, stringent upper mass limits of undetected planets for a range of periods can also provide constraints on planet-formation theories.

Table 8. Summary of Theory and Modeling Programs Relevant to the Estimation of the Frequency of Earths

Science Objectives	Timeline	Research Area	Science Program
Understanding of the Frequency of Earths	2004–2010	Planet formation	Physical conditions for planet formation; timescales; efficiency of planet formation; barriers to formation
Evolution of planetary configuration	2004–2015	Dynamical modeling	Evolution after planet formation; dynamical filling factor
Earths in the presence of giant planets	2004–2015	Planet formation	Formation and preservation of Earths in the presence of known giant planets
Evaluate circumstantial evidence for Earths	2005–2010	Literature	Combine all known threads of evidence
From dust to planets	2004–2015	Model the coagulation process	Understand growth from dust to km-size objects, and barriers to growth; interpretation and extrapolation of known exozodiacal systems
Thermal evolution of planets	2005–2015	Modeling of planetary interiors and atmospheres	Differentiation of materials; coupling between atmosphere and surface physical processes
Observation and modeling archive	2004–2015	Consolidated archives and databases	Repository of information on the search for planets – for both observers and theoreticians

3.7 Summary: Opportunities, Risk, and Priorities

On the timescale of TPF-C and TPF-I, it is unlikely that any other missions will directly detect light from a terrestrial planet. Our current knowledge of terrestrial planets is limited to our own Solar System and to planets around pulsars. An improved understanding of the formation and evolution of giant planets is essential to a complete picture of how terrestrial planets form, and whether their orbits are stable over long timescales. For gas-giant planets, surveys using radial velocity, astrometry, stellar transits, and microlensing techniques offer possibilities of increasing our understanding of extrasolar planetary systems. Of these techniques, the ones most likely to make a significant contribution to TPF are the radial velocity surveys and the space-based transit missions.

Recommendations relevant to the approaches that have been outlined above can be summarized as follows:

- *Radial velocity monitoring* is a proven technique that will yield more long-period planets as the time-baseline of observations continue to increase. There is a shortage of high-resolution échelle spectrometers for radial velocity survey work. These instruments are currently oversubscribed

with planet searches and efforts to cull binaries for reference stars and grid stars for interferometry. New spectrometers represent significant upgrades for existing, under-utilized 2–3-m class telescopes. This may have the added advantage of shifting the research load on larger telescopes to work that is uniquely possible with a larger aperture. Surveys conducted by robotic telescopes in remote sites with excellent seeing also represent a good investment as workhorses for extrasolar planet detection.

- *Ground-based transit surveys* for gas-giant planets should be encouraged; this technique is still not fully exploited. In particular, the potential of a robust, worldwide network of dedicated wide-field transit-search telescopes should be investigated since the follow-up studies enabled by these bright targets are very exciting.
- *High contrast imaging surveys* for brown dwarf and giant planet companions have the potential to inventory the major bodies in the outer (> 5 AU) region of nearby planetary systems, without waiting for a full orbital period to elapse. Such investigations can provide the full picture of the end products of planet formation in general, and for the TPF target stars in particular. Development of specialized wavefront sensing and control instrumentation is needed to advance both ground and space telescopes to the required contrast performance limits.
- A *comprehensive theoretical investigation* into many aspects of the formation and evolution of planets and planetary systems must provide the framework within which to understand the necessarily incomplete observational results. Examples of such investigations are listed in Table 8. The combination of the existing near-term radial velocity and transit programs with theoretical insights into orbital stability, planetary migration, and the relationship between gas giants and rocky planets will give us the confidence to move forward with TPF.
- *Other techniques*, such as astrometry and microlensing, all contribute to the overall picture. Each technique has particular advantages. The synthesis of all these techniques within a broad theoretical framework is critical to appropriate development of TPF-C and TPF-I and subsequent interpretation of data from the missions.

The anticipated progress with related ground-based and space-based missions is shown in Fig. 11. Perhaps the biggest risk to improving our understanding of extrasolar planetary systems would be the failure of the COROT or Kepler missions to be launched successfully or their performance at less than expected levels. In this case, TPF-C would not benefit from improved statistics of terrestrial planets prior to entering Phase B/C/D, anticipated in 2010. Mitigating against this risk will be continuing progress in making radial velocity measurements to more precise levels and on longer temporal baselines. By 2010, radial velocity measurements will be able to detect planets as small as 5–10 Earth masses inside 1 AU, enough to give stronger support for theoretical estimates of η_{\oplus} . If η_{\oplus} is high enough (>0.1), then COROT has a good chance of detecting multiple Earth-like planets.

3.8 Assessment of Progress

In future versions of this document, an assessment of progress will be included here.

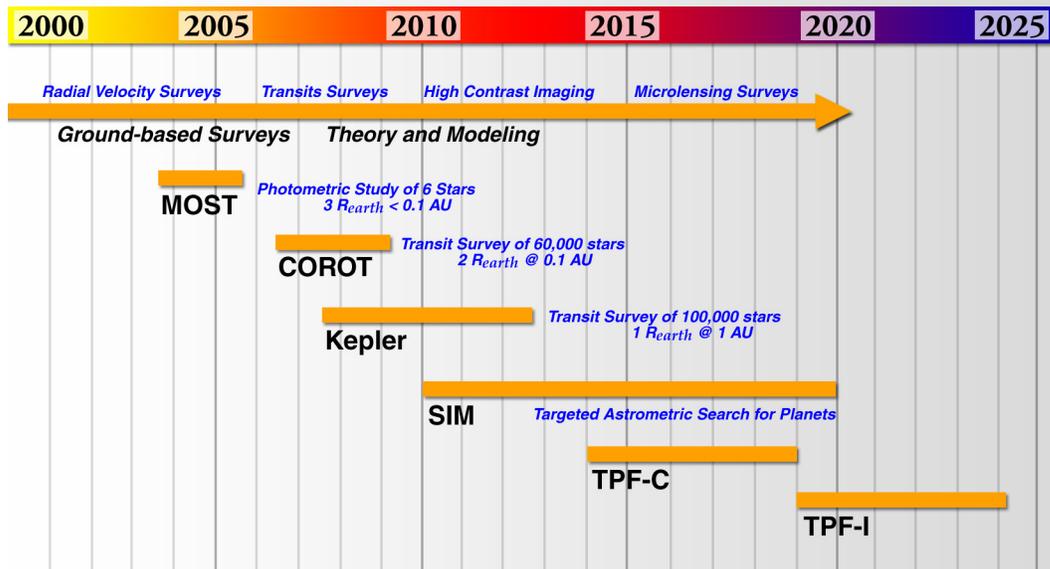


Figure 11. Timeline for ground and space observations contributing to our understanding of the characteristics of extrasolar planetary systems. By 2010, results from the COROT and Kepler missions will have refined our knowledge of the frequency of Earth-like planets and thereby assist in defining the scope of TPF-C prior to its Phase B.

4 Exozodiacal Dust and the Search for Planets

Relevance to TPF

Exozodiacal dust is of major importance to building a better understanding of the formation and evolution of planetary systems. However for planet detection, exozodiacal emission can be a bright background that TPF-C and TPF-I must overcome in searching for planetary signals. Both the mid-infrared interferometer and the visible coronagraph architectures are affected by the presence of dust emission. A more complete understanding is, therefore, of great importance prior to the earliest mission concept review.

Metrics for Decision Making

The advantage of coronagraphs versus interferometers depends on exozodiacal light levels and the distance to the individual targets, and will be assessed in greater detail in the ongoing trade studies. The effect of increased levels of exozodiacal emission is to increase the integration time needed to detect a planet. The performance of both coronagraphs and interferometers degrades as the level of exozodiacal light and the distance to the star increases. However, below about 10 times the Solar-System levels, the observing-time penalty is not severe — an increase of a factor of up to 3.5. If it were found that most potential target stars had levels of exozodiacal light much greater than 10 times the Solar-System level, longer integration times would need to be accounted for in the mission design.

Schedule and Deliverables

In Pre-Phase A, the mission concept review — assessing technological readiness of the coronagraph or interferometer designs — is the highest priority issue that must be addressed. Thus, a fundamental question to be resolved prior to the review is to determine the number of stars that are likely to have exozodiacal levels less than 10 times our Solar System. A preliminary target list is also needed, along with exozodiacal light measurements or limits for each target. Such measurements are needed about a year before TPF-C enters Phase A. This will allow the information to contribute to the mission concept review in a timely manner.

4.1 Observations of Exozodiacal Dust

Current State of the Art

Based on IRAS survey results, about 15% of nearby normal main-sequence stars of all spectral types have been found to have circumstellar dust with characteristic temperatures almost always less than 150 K. These dust envelopes may be connected to planetesimal belts resembling our Kuiper Belt. Stars with dust hotter than 150 K are rare, but our knowledge is limited by the surveys carried out to date. About eight main-sequence stars have been found that have warm, detectable dust within the central “hole.” The most prominent of these stars is β Pictoris, with inferred temperatures of up to at least 350 K. Some stars with ages estimated to be older than 1 Gyr have detectable far-IR excesses, evidence that planetesimal dust can persist well into the main sequence age. The image shown in Fig. 12, taken with the Advanced Camera for Surveys on the Hubble Space Telescope, and the image in Fig. 13 (page 44), from the Spitzer Space Telescope, illustrate the current state of the art in imaging circumstellar disks.

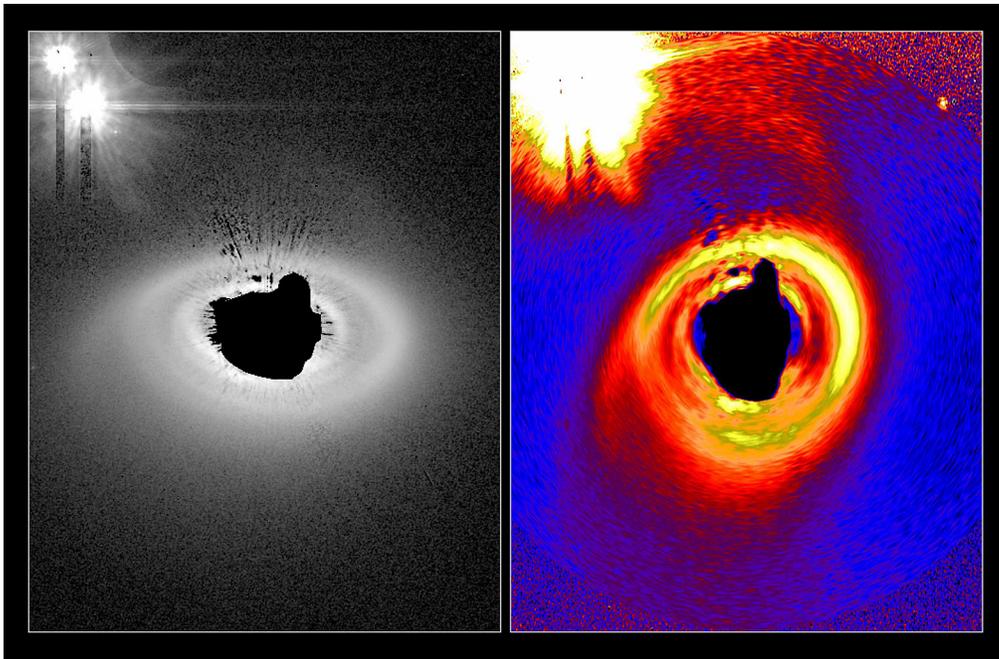


Figure 12. Observations of the circumstellar disk around HD 141569A, taken with the High Resolution Camera coronagraph on the Hubble Space Telescope's Advanced Camera for Surveys. The photo on the left is a processed visible-light image. In the photo on the right, the disk has been geometrically altered to simulate a face-on view, and false-color has been added to enhance the disk structure. The images show that the disk's structure is much more complex than previously thought, having a tightly-wound spiral structure. The outer regions of the disk reveal two diffuse spiral arms, one of which appears to be associated with the nearby binary system, HD 141569BC.

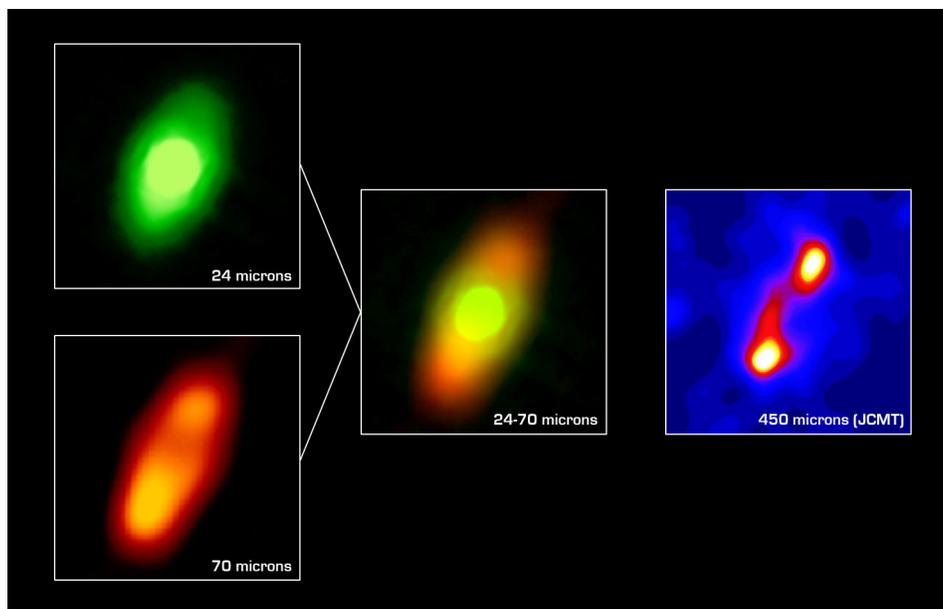


Figure 13. Image of the dust disk around Fomalhaut, taken with the multiband imaging photometer of the Spitzer Space Telescope. The 70-micron image (lower left) clearly shows an asymmetry in the dust distribution, possibly due to collisions between asteroids. At 24 microns (upper left) the center of the ring is shown to be not entirely empty. This warm inner disk is analogous to our own zodiacal cloud, but with considerably more dust.

Expected Near-term Progress

The next few years will yield significant progress on the question of exozodiacal emission around TPF targets. The most important near-term mission will be the Spitzer Space Telescope which will make sensitive measurements of exozodiacal clouds at wavelengths of 24 μm , 70 μm , and 160 μm , spanning typical temperature ranges of 40–200 K and corresponding to distance scales of a few to a few hundred AU from the parent star. The sensitivity to exozodiacal emission will be limited by Spitzer's photometric accuracy since the satellite has inadequate angular resolution to resolve these disks except in a few particularly favorable cases. As shown in Figure 14, Spitzer will be able to detect or set limits on excesses that are less than 25% to 50% above the stellar photosphere (3σ). At a wavelength of 24 μm , this limit corresponds to a factor of 100 to 1000 times the level of dust emission in our own solar system in the distance range of 1 to 10 AU where 100–200 K dust is located for a solar type star. At longer wavelengths, the photosphere is weaker, and the corresponding limit is only 1–10 times the level of the dust level in our solar system for ~ 50 K dust located at a distance of 10–100 AU. Spitzer is already scheduled to make these observations for over 200 prime TPF targets. Observations of an additional 100–200 potential TPF targets are likely to be selected in the coming years through the General Observer program.

While Spitzer will make excellent measurements of Kuiper Belt analogs in other solar systems, it will detect only the most extreme analogs of dust like our own zodiacal cloud. The next round of information will come from the various ground-based nulling interferometers planned to come into operation over the next few years, including the Keck Interferometer, the LBT-I, and the VLTI/GENIE. Starting with Keck observations in 2005, the first reconnaissance of exozodiacal clouds in the habitable zones of nearby stars

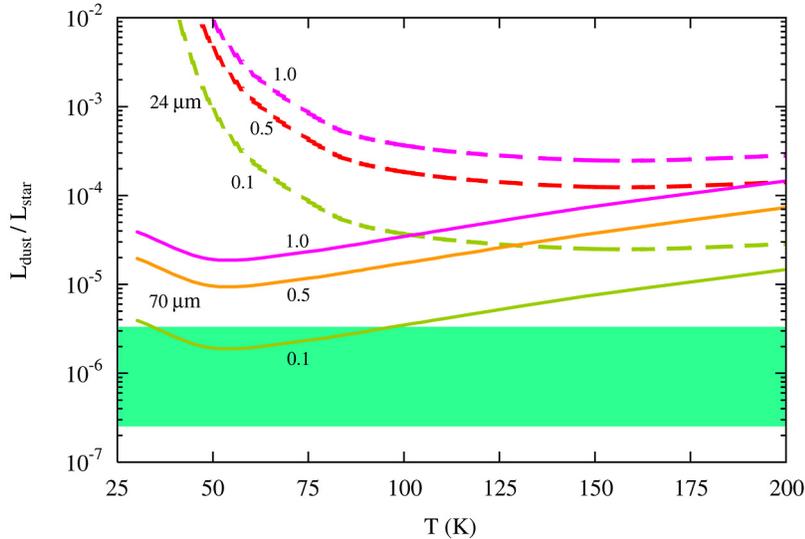


Figure 14. The fraction $L_{\text{dust}}/L_{\text{star}}$ is shown as a function of dust temperature (T_{dust}) for different wavelengths and limits on the photometric excess as a fraction of the photospheric emission for a G2 star. Typical Spitzer observations will reach a fractional excess of 0.3–0.4 (3σ) at 70 μm (solid lines) and ~ 0.2 (3σ) at 24 μm (dashed lines). The shaded area shows estimates of the optical depth of dust in our Kuiper (~ 50 – 80 K) and zodiacal (150–250 K) clouds.

will have a sensitivity of about 10 times the level of our solar system. With their long baselines, the Keck Interferometer and the VLTI will detect emission between 0.1–1.0 AU for a star 10 pc away. Figure 15 (page 46) illustrates the response of the Keck Interferometer. The LBT-I, with its shorter 14-m baseline, will detect emission at larger distances from the star, in the range of 0.5–5 AU. In their first years of operation these facilities will observe critical samples of stars to assess the strength of the zodiacal emission in and around the habitable zone. This will help determine if there is a significant problem with the average level of emission around TPF targets — whether many or all stars have more than 10 times level of our solar system. In the longer term, these facilities will complete surveys to the most sensitive level to characterize all possible TPF targets.

Neither ground-based adaptive optics nor coronagraphic observations with HST can currently work at dust optical depths less than about a third of that of β Pictoris. However, if a 2-m class space adaptive optics coronagraph mission were implemented, as may be possible around 2010 within the scope of a NASA Discovery mission, then imaging of disks would be possible down to about 10 times our Solar System level in the Kuiper Belt region in hundreds of targets. Images of disks and their internal structures would be a key science return from such a mission.

In the longer-term, an ideal instrument to image the new disks uncovered by Spitzer will be the Atacama Large Millimeter Array (ALMA), which is expected to begin operation late in this decade. With 64 antennas of 12-m aperture spread across baselines extending to 10 km, ALMA will achieve a spatial resolution of 30 mas (0.5 AU at β Pictoris; 4 AU in nearby star-forming regions). ALMA will provide detailed maps of the density, kinematic structure, and chemical structure of protoplanetary disks in molecular line emission; and of the dust continuum emission of nearby debris disks. With no stellar contrast problem at these wavelengths, ALMA should map more disks in more detail than any prior astronomical facility.

Contributions to TPF Precursor Science

It is important that the complete list of potential TPF target stars be well characterized. A crucial aspect of this work will be to determine the presence or absence of dust disks around these stars. Although selected stars may be studied through individual peer-reviewed proposals, a program coordinated between NASA and ESA is needed that will make the best use of missions whose lifetime is limited. It will be important to ensure that the *complete* sample of potential TPF targets (~250 stars) is observed through missions such as Spitzer and Herschel.

The combination of high resolution imaging of debris disks (Spitzer, Herschel, HST, JWST, Keck, LBT, and VLT Interferometers) with theoretical investigations of the dynamics of such systems might lead to indirect detection of planets by gravitational perturbation of dust morphology.

Our estimate of the frequency of Earth-like planets may be improved through observations of the structure and evolution of dust and gas within debris disks in various star-forming environments. This would yield information including the total mass, the surface density, the temperature, the composition, and distribution of gaps in these disks, leading to a greater understanding of the mass transfer rate, the compositional changes, and the persistence time scales of material found there.

The greatest source of confusion in the background of a TPF target star may not be background stars or galaxies, but structure in the star's exozodiacal dust disk. Follow-on observations by a space-based adaptive optics coronagraphy or with ALMA could provide detail of nearby exozodiacal disks in advance of the launch of TPF-C and TPF-I.

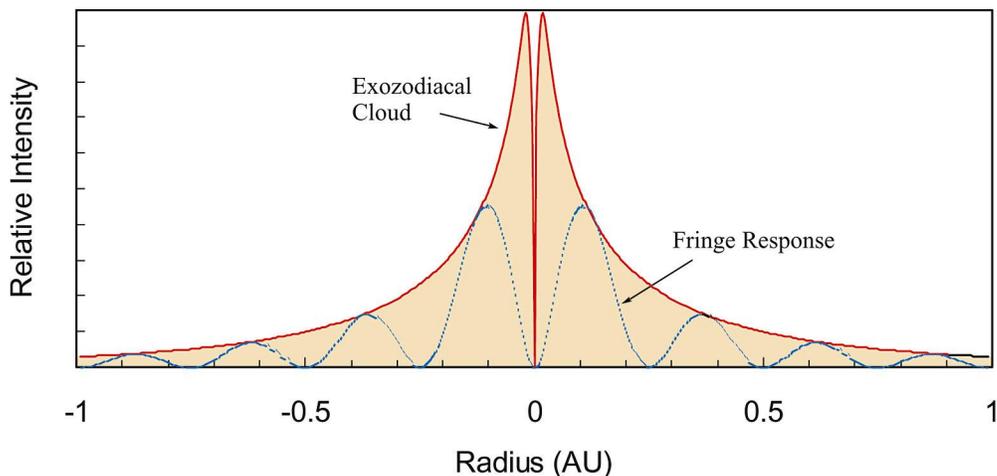


Figure 15. Cross-sectional view through an edge-on exozodiacal cloud at a distance of 10 pc, showing the emergent flux (solid curve), and the flux transmitted by the 10 μm fringe pattern of the Keck Interferometer in the nulling mode (dotted curve).

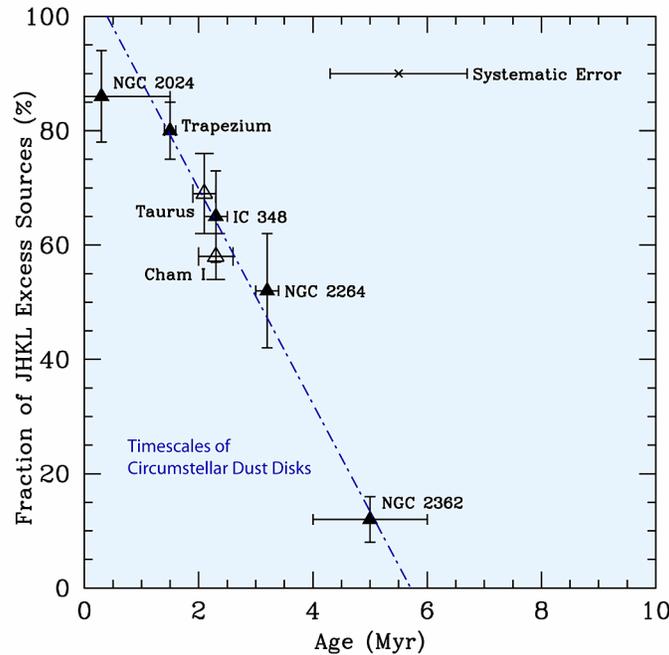


Figure 16. Brightness of exozodiacal dust disks as a function of age. The mean brightness of infrared excess in stellar clusters is plotted as a function of the cluster age. The infrared excess of sources is assumed to correspond to dust disks, indicating the disappearance of the disks at an age of roughly 6 million years. This is the timescale for essentially all stars in a cluster to lose their disks, and may set an approximate upper limit for the mean timescale of planet formation.

4.2 Theory and Modeling of Exozodiacal Dust

The formation and evolution of debris and zodiacal disks can be better understood through applications of theory and modeling. These models must of course be consistent with observations, as illustrated in Fig. 16, which may for example place upper bounds on the timescale of planet formation. Moreover, the detection of dust and disk structures around stars will provide tantalizing circumstantial evidence for the presence of planetesimals. We may be able to then estimate the number and frequency of planets from the observable properties of debris and zodiacal disks. Theoretical analysis is also important for determining the possible difficulty of detecting terrestrial planets set within a background of diffuse emission.

Current State of the Art

Dynamical evolution of debris disks

Theoretical models are needed to understand the dominant processes that regulate the evolution of debris disks around stars of various ages. Physical effects that need to be considered include the interaction between residual dust particles and gas with stellar radiation, and particles' growth and fragmentation associated with their collisions. Models are needed to describe the origin and distribution of the residual planetesimals that may exist in debris disks. In the outer Solar System, the orbital distribution of Kuiper

Belt Objects suggests that a large fraction of planetesimals are scattered outward as a consequence of secular perturbation by giant and terrestrial planets. These models will have implications on the potential extent of planetary systems and the planet formation efficiency and rate near the habitable zone. The dynamical evolution of comets, and therefore of volatile and organic material, also needs to be examined for planetary systems with a range of dynamical filling factors and in a variety of stellar environments. The delivery of organic material, and the giant impacts of planetesimals, may determine the evolutionary paths of life on habitable planets.

Embedded planets in debris disks

Some debris disks such as that around HD 141569 have sharp edges with apparent gaps while others such as that around β Pictoris have warps. These structures are suggestive signs of embedded planets. Theoretical analysis is needed to determine the origins of these disk structures and the possible existence of planets at such large distance from their host stars. Numerical simulations will be useful to model observable features which may provide quantitative data on the mass and orbit of the embedded planets and the surface density distribution of residual particles and gas.

Survival of debris disks in stellar associations and clusters

Theoretical analysis should be carried out to assess the survival and replenishment of dust in debris disks. The structures of outer regions of debris disks are sensitive to external perturbations. In stellar associations and clusters that contain massive stars, photo-ionization of gas in the outer disk may limit the spatial extent and duration of planet formation. Theoretical analysis is also needed to assess whether field stars would destabilize the orbits of planets and residual planetesimals leading to the disruption of debris disks or the fresh injection of residual planetesimals into the outer debris disks.

Zodiacal light

Numerical simulations have already been made assessing the probability of residual planetesimal collision and the production rate of particles that contribute to hot exozodiacal reprocessed radiation. The primary motivation for further analysis is to assess the intensity of zodiacal light for systems that are most likely to contain Earth-size planets in the habitable zone. This assessment will be useful for estimating the contrast

Table 9. Ground and Space-based Missions Relevant to the Study of Exozodiacal Dust and the Search for Planets

Science Objectives	Timeline	Supporting Facility	Science Program
Characterization of Kuiper Belt Emission	2003–2008	Spitzer	MIPS survey of ~250 stars
	Ongoing	HST/ACS	Coronagraphy of the brightest debris disks
	2006–2011	Herschel/SOFIA	Maps of bright dust disks
Maps of Dust in Habitable zone at 10 μ m	2005–2010	Keck-I	Northern stars, resolution of 13 mas to 10x Solar System
	2006–2016	LBT-I	Northern stars, resolution of 74 mas to ~1x Solar System
	2008–2017	VLTI	Few hundred southern stars, as precursor science for Darwin

between the planets and the background emission. Further simulation of dynamical interaction between zodiacal dust and planets with various orbital configurations around different types of stars will be useful to identify signs of embedded planets.

Expected Near-term Progress

As shown in Table 9, the next few years will see a wealth of new observational data on exozodiacal clouds, most importantly and most immediately from Spitzer. This will include measuring lower levels of exozodiacal emission than have previously been possible (<100 times the level of our own Kuiper Belt) around hundreds of stars with a wide variety of ages (millions of years to billions of years), metallicities, presence of planetary systems, etc; spectroscopy of hundreds of disks, spatially resolved for a few cases, revealing information on the composition and size of exozodiacal material. A few years later, ground-based interferometers (Keck, LBT-I, and VLTI) and large far-IR telescopes (SOFIA and Herschel) will map exozodiacal emission in the habitable inner reaches of other planetary systems. A robust theory program will take in all this information to constrain better our understanding of the formation and evolution of solid material in planetary systems, particularly the formation of rocky bodies like the Earth. This synthesis of theory and observation will also advance our understanding of the environment of the early Earth when life originated using material from the final epoch of impact and infall.

Contributions to TPF Precursor Science

A program of theory and modeling of exozodiacal dust is essential to knit together the disparate observational datasets described above into a coherent whole that we can use to extrapolate the detailed knowledge needed for TPF. To what extent is the presence of an exozodiacal disk a signpost of the presence of large rocky bodies (asteroids, comets, moons, Earths)? How do planets produce wakes and other structures in the exozodiacal cloud that could be a source of confusion in the search for planets? What processes produce the large-scale structure of the exozodiacal cloud, and how does that structure affect the detectability of planets?

4.3 Summary: Opportunities, Risk, and Priorities

Imaging of dust disks is a rapidly growing field, as indicated by the timeline of related ground-based and space-based missions shown in Fig. 17 (page 50). HST coronagraphy will continue to resolve high optical-depth reflected-light disks. Spitzer will study a large sample of stars for disks on scales of the Kuiper belt. Spitzer began its surveys for Kuiper Belt disks and bright inner zodiacal clouds in late 2003 with first results to be available by late 2004. The Keck interferometer will begin measurements of exozodiacal clouds (a few times our Solar System level) in 2005, to be joined shortly thereafter by LBT-I and VLTI. Searches for disks around TPF target stars are of inherent scientific interest and will likely occur naturally through the peer-reviewed proposal process on all these facilities.

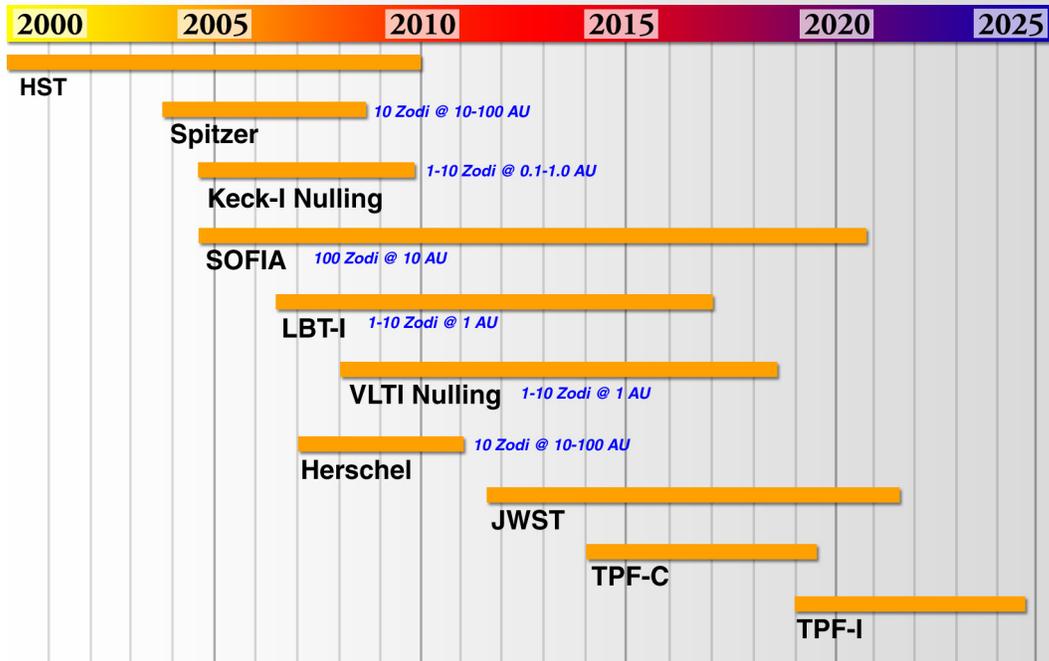


Figure 17. Timeline for ground and space observations contributing to our knowledge of exozodiacal dust and the search for planets. By 2006, observations with Spitzer should refine our understanding of the brightness of dust around nearby stars and thereby provide information to support the TPF architecture decision prior to entering Phase A.

It will, however, be important to ensure that the *complete* sample of potential TPF targets (~250 stars) is observed by missions of limited lifetime, e.g. Spitzer and Herschel. Thus, the TPF and Darwin Projects should work with NASA and ESA to ensure that a coordinated observing program to observe TPF target stars is carried out. Most of the obvious targets are already scheduled for observations by Guaranteed Time or legacy observers. But any additional stars suggested as particularly important by the TPF-SWG should be observed during the open time on Spitzer. This information should be augmented by higher angular resolution observations with ground-based interferometers (operating in a two-telescope nulling mode) and observations with the Herschel Space Observatory. This information will be adequate to assess the importance of exozodiacal emission for the design of TPF-C and TPF-I.

With the successful launch and initial operations of Spitzer, a major source of risk to the program has been removed. It is now highly likely that we will be able to survey many hundreds of potential TPF targets with Spitzer. Since these observations are of high scientific interest, it is probable that these data will be obtained with little need for intervention into the normal time allocation processes. Other areas of risk include the failure of one of the interferometers to perform at the required level of sensitivity for observations of dust in the habitable zone. This risk is mitigated by the fact that there are three on-going interferometer programs: Keck-I and LBT-I in the Northern Hemisphere, and VLT-I/GENIE in the Southern Hemisphere. In addition, both SOFIA and Herschel will add important observations at intermediate angular resolution between now and 2008.

4.4 Assessment of Progress

In future versions of this document, an assessment of progress will be included here.

5 Characteristics of Stars That May Harbor Earth-Like Planets

Relevance to TPF

What are the characteristics of stars, such as the Sun shown in Fig. 18 as well as stars of other spectral types, that make them suitable hosts of habitable worlds? Amongst stars that support Earth-like planets, what types of stellar parameters will enhance our ability to detect and characterize their planets? The answer to these questions will help develop preliminary target lists that will guide the execution of TPF-C and TPF-I. In the near-term the target list will influence the mission concept reviews — through the assessment of exozodiacal light levels around nearby stars — and in the long-term will enhance the probability that TPF will discover signs of Earth-like life on planets around nearby stars.

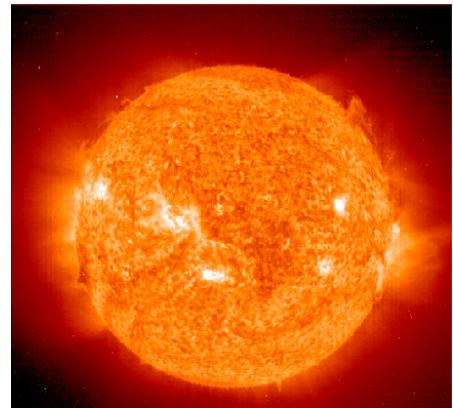


Figure 18. 304 angstrom image of the Sun, from the SOHO Extreme Ultraviolet Imaging Telescope.

Metrics for Decision Making

The target list will be developed using criteria that define the bounds of stellar properties necessary to support habitability. These properties and associated criteria are described in more detail in section 5.1.

Schedule and Deliverables

A preliminary, although well-developed, target list is necessary in Pre-Phase A to assist the architecture design teams in their preparation for the mission concept review. With a preliminary list, the feasibility of an architecture design can be realistically assessed to provide support for entry into Phase A.

During Phase A, a more detailed list is necessary to allow an initial design of each TPF mission and to set the scope of each observatory: the list of candidate stars will need to be estimated so that the angular resolution and sensitivity can be calculated. This will allow instrument parameters to be determined that will provide support for entry into Phase B.

5.1 Properties of Stars That Harbor Earth-Like Planets

The astrophysical properties of interest in assessing habitability include:

- Stellar Age
- Evolutionary Phase
- Spectral Type/Mass
- Variability
- Metallicity
- Galactic Kinematics
- Multiplicity
- Giant Planet Companions

Each astrophysical property of a star has an influence on the existence and longevity of a circumstellar habitable zone. The TPF target list will be developed to identify those nearby stars that are most likely to harbor Earth-like planets. As illustrated in Fig. 19, this will be done beginning with a list of all nearby stars and reducing the list using suitable criteria. The selection shown in Fig. 19 is one example of how the list might be derived. The sky distribution of targets shown in Fig. 20 is from a separate list. The ongoing focus of effort will be to set appropriate limits of habitability for each stellar property under consideration.

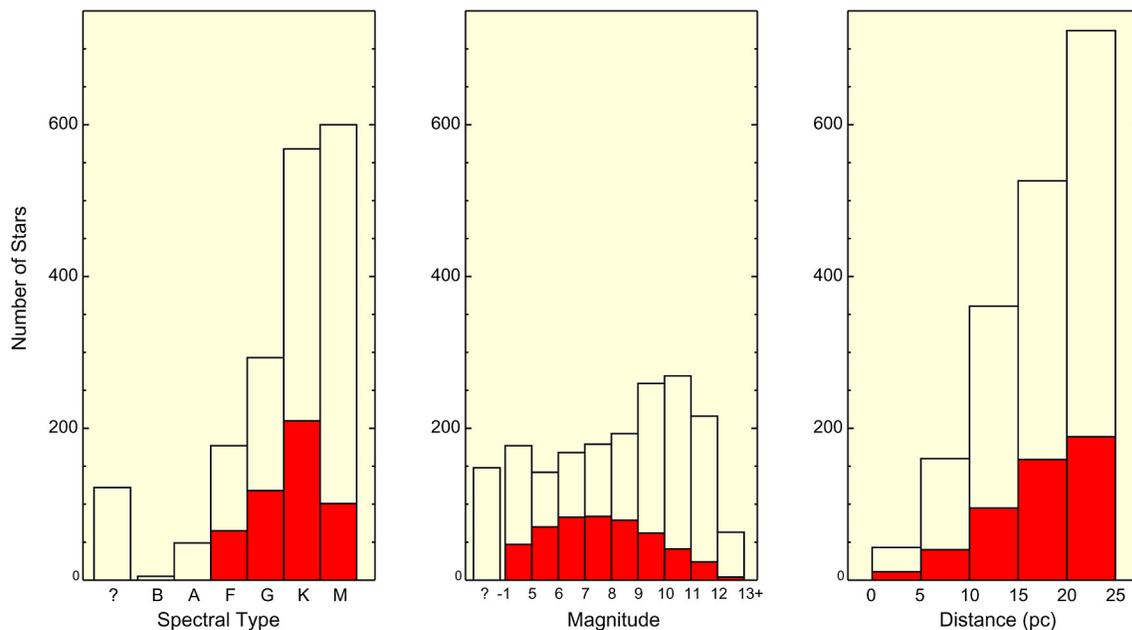


Figure 19. Distribution of potential TPF target stars as a function of spectral type, magnitude, and distance. All stars within 25 pc of the Earth (outlined above) were initially selected from the Hipparcos catalog, by choosing only those with a parallax of 40 mas or greater. Stars of spectral type F, G, K, or M were kept, and within those groups stars were rejected if they had composite or variable spectra. Only luminosity class V stars were then retained. All stars with specific variability types were removed. Stars were then also rejected if they had Hipparcos double or multiple flags or Hipparcos Annex flags of G, O, V, or X. Stars were also removed if they had a companion (or likely companion) within 10 arcseconds. The remaining 494 stars are shown by spectral type, magnitude, and distance, in the red shaded areas above.

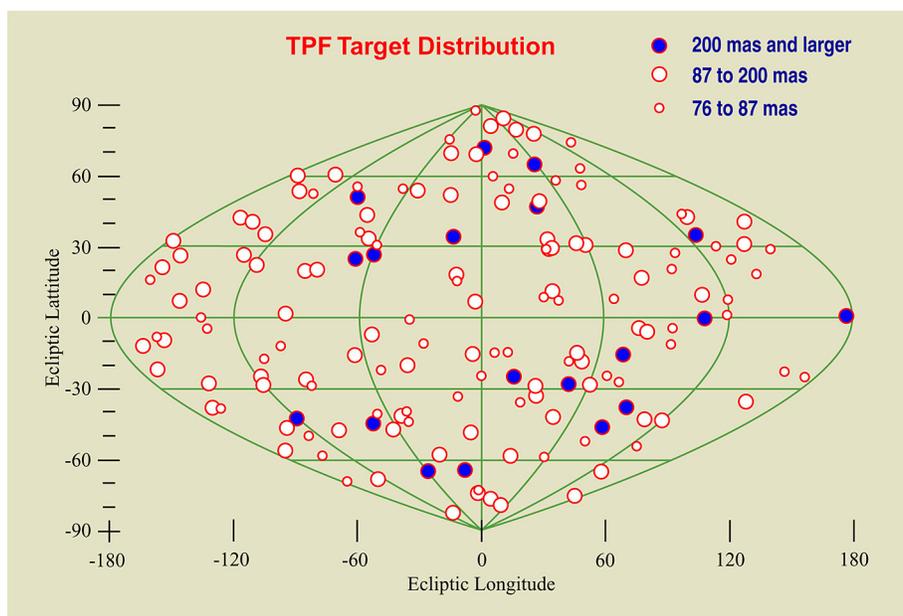


Figure 20. Distribution of 160 of the nearest TPF target stars. The likely angular separation of a terrestrial planet from its host star is indicated by the symbols shown in the plot. The small open circles are for terrestrial planets 76 to 87 mas from the star. The larger open symbols are for terrestrial planets 87 to 200 mas, and the large blue circles are for terrestrial planets separated by 200 mas or more from their star.

Stellar Age: For very young systems (especially less than ~ 1 billion years), terrestrial planets may experience frequent life-suppressing impacts, and spectral biosignatures (e.g., oxygen, ozone, and methane) are less likely to have affected the planetary characteristics on a scale that is detectable to TPF-C or TPF-I. On Earth, although abundant biogenic methane may have been present in our atmosphere prior to 2 billion years ago, the rapid rise of oxygen due to photosynthetic organisms did not occur until about 2 billion years after formation. This lower atmospheric oxygen content for young planets, in combination with the increased UV and X-ray emissions from young stars, makes it less likely that life forms would be adequately ozone-shielded from harmful radiation. Finally, exozodiacal dust emissions will be greater for younger systems, especially those at high orbital inclinations, which may make terrestrial planets less detectable to TPF-C or TPF-I.

Evolutionary Phase: Evolutionary phase determines the width of the continuously-habitable zone, which shrinks as stars increase in brightness during their main sequence (hydrogen-burning) lifetimes, and disappears altogether when stars rapidly transition into helium-burning red giants. The red giant phase itself lasts only about one-tenth as long as the main sequence lifetime, leaving little time for a new genesis of life on more distant terrestrial planets or moons.

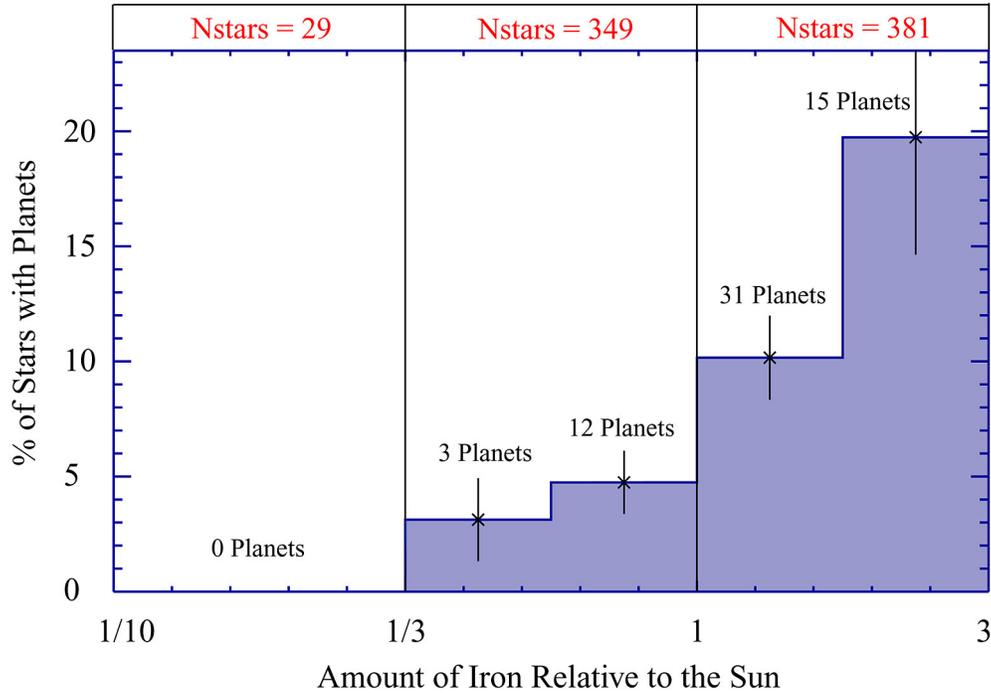


Figure 21. The percentage of stars with gas giant planets as a function of the iron content of the stars. 754 stars were grouped according to their iron content relative to the Sun. Stars with large amounts of iron are more likely to harbor gas-giant planets than iron-poor stars.

Spectral type and Mass: Stellar mass and spectral type are related to both age and evolutionary phase, in that all stars more massive than about twice the mass of the Sun leave the main sequence at an age which is younger than about one billion years. Thus, the one billion year continuously habitable zone vanishes for all main sequence stars earlier than about F0.

Stellar Variability: Stellar variability, either stochastic (i.e., flaring) or periodic, may cause climate changes or UV and X-ray emissions that are harmful to life. During the 11-year solar cycle, the Sun changes in brightness by 0.1 percent, with about this same level of stochastic variability during Solar Maximum due to flaring. This activity level appears to be harmless. However, the Medieval Warm Period of the 1100s and Maunder Minimum in the 1600s resulted from longer timescale Solar variations as large as 0.5%, a level of variability which is not deleterious, but does begin to noticeably impact both climate and biology. Stars exhibiting flaring or periodic variability in excess of about 1% may, therefore, not be habitable. M-type stars are of special concern here, given their very nearby habitable zones and their tendency for luminous flares at high-energy wavelengths. While not all M stars flare, non-flaring M stars may be very old, and therefore of lower metallicity.

Metallicity & Galactic Kinematics: Stellar metallicity is a reflection of the metal content of the parent cloud from which the star formed, and therefore indicates the likelihood that terrestrial planets (with their very high iron and nickel content) formed as well. So far, radial velocity searches for planets have verified the correlation between stellar metallicity and the presence of gas giant planets, as shown in Fig. 21.

Metallicity and kinematics are also related, in that older stars tend to have both lower metallicity and higher velocity dispersion. For stars with $[\text{Fe}/\text{H}] < -0.4$ (about 40% solar abundance), the U, V, and W Galactic velocity dispersions increase by a factor of two. Thus stars that are not kinematical members of the thin disk of the Galaxy are less desirable targets for TPF, unless spectroscopic data are available indicating a metallicity greater than about half the metallicity of our Sun. Highly elliptical orbits through the Galaxy may be of further concern in that these stars will pass through spiral arms more frequently, where high-energy radiation, cosmic rays and even interstellar dust densities may affect planet climate and habitability.

Multiplicity & Giant Planet Companions: The presence of stellar and giant planet companions can interfere with the dynamical stability of terrestrial planets in the habitable zone, so all potential TPF targets should be carefully examined for low-mass companions, e.g. by radial velocity measurements. Giant outer planets in circular orbits may contribute to the long-term stability of the habitable zone by dynamically shielding it from cometary bombardments. Very wide binaries do not pose a special concern (indeed, some known giant planets orbit within wide binary systems) unless the additional shot noise from the second star interferes with TPF observations. Some low-eccentricity giant planet companions that orbit within the habitable zone are known and may make interesting first targets for testing the instrument on a relatively bright planet at the appropriate angular distance from the central star.

5.2 Observations of Stars

Indicators of stellar youth all arise from the fact that stars are born with relatively high rotational velocities (~ 100 km/s), and slow down in a predictable way via magnetic braking. This rotation, combined with convection zones in late F- through M-type stars, drives chromospheric activity and X-ray emissions, which also decrease with time as rotation slows. Projected rotational velocities (which indicate a minimum on the true rotational velocity) greater than 10 km/s, and X-ray emissions in the ROSAT PSPC 0.1–2.4 keV energy range greater than 2.1×10^{28} erg/s, are both consistent with ages less than 1 billion years for G-type stars. The R'_{HK} calcium II H- and K-line chromospheric activity indicator tends to vary over time as a given star goes through activity cycles (like the 11-year solar cycle), but $\log R'_{\text{HK}} > -4.75$ indicates a chromospherically active star that is not more than about 2 billion years old. With accurate photometry and metallicity data, isochrone-fitting can be used to date stars, but this method is also uncertain by ~ 1 billion years, with uncertainties increasing for later-type stars.

The Hipparcos mission was able to detect flux variations in the Hp bandpass of $\sim 3\%$ (a level of variability at least five times greater than that of the Sun) and several variability flags are included in the Hipparcos Catalogue. Spectroscopic analysis, such as that being carried out by Houk for stars in the HD catalog, indicating emission lines (“e” flags, e.g. “M5Ve”) or variable lines (“var” flags) are also useful in noting variable stars.

Stellar metallicity can be estimated either through spectroscopic measurements or Stromgren photometry. The two methods agree with one another quite well to within a few tenths of a dex in $[\text{Fe}/\text{H}]$ for metallicities greater than about $[\text{Fe}/\text{H}] = -1.5$. TPF targets should have metallicities of at least half solar.

All potential TPF target stars should be searched for low luminosity companions through radial velocity measurements. For known binaries, the angular separation of the two components should be at least 10" to prevent the signal from a terrestrial planet from being overwhelmed by shot noise from the secondary star. The linear separation of the two components is also of concern for the dynamical stability of the habitable zone, and while the critical separation is dependent upon the eccentricity of the binary orbit and the mass ratio of the two components, these parameters are not usually known for longer period visual binaries. A fairly safe rule of thumb is that the observed linear separation should not be less than about ten times the size of the habitable zone for TPF stars.

Finally, there is a serious need for observational precursor science within the target selection effort for TPF. Nearly all of the stars within 30 pc have missing information for the habitability indicators listed above. A concerted effort should be made to photometrically and spectroscopically monitor all main sequence A-through M-type Hipparcos stars within 30 pc, for the sake of determining metallicities, ages, kinematics, variability, and the presence or absence of companions and identifying the most favorable TPF targets.

5.3 Searches for Brown Dwarf and Giant Planet Companions

It may well be that the most favored TPF target systems will be those with exterior giant planets (indicating the presence of a planetary system), but without the dynamically disruptive giant planets near 1 AU. The complete system of stellar, sub-stellar, and jovian planetary companions associated with each TPF target star should be characterized to enable an assessment of the dynamical environment of the terrestrial planets that TPF-C or TPF-I might find, and to define the formative history of each individual planetary system. The recent discoveries of wide stellar companions to the planet-bearing stars υ And, HD 114762, τ Boo, and 16 Cyg, and wide brown dwarf companions to the solar analogs HR 7672 and ϵ Indi (the latter just 3 pc away), demonstrates how vastly incomplete our knowledge is of companions to the likely TPF target stars. Depending on the details of the initial mass function for binary stars, a large population of cool, low-mass brown dwarf companions could be present and have remained undetected by studies to date. Beyond 5 AU orbital distances, the population of brown dwarf and giant planet companions has yet to be characterized. Direct imaging is the only way to make an inventory of the outer planet region of the TPF target stars on TPF's programmatic timescale.

A program of very high contrast imaging should be initiated for all nearby FGK stars that are likely TPF targets, with the near-term goal of detecting all companions earlier than spectral type T, and the medium-term goal of detecting all companions with mass greater than or equal to that of Jupiter. A database of non-detection upper limits from previous imaging work should be assembled and maintained to guide future survey work. Observational progress in the companion search will come from additional HST/NICMOS work, from existing AO and future extreme AO systems on ground-based telescopes, from Spitzer and JWST, and from future 2-m class space coronagraph missions. A by-product of the companion search will be an initial indication of any "bright" sky background objects that might confuse TPF's work at still fainter sensitivity levels.

5.4 Observations of Background Fields

TPF-C and TPF-I must detect light from planets in the presence of confusing signals. Dust disks have already been mentioned as an important research area for TPF precursor science. Imaging of background fields is important also, as is modeling of the instrument response to fields with emission other than that from the planet. In some cases, the results may influence the final choice of TPF target stars.

Both conventional HST coronagraphic imagery and off-the-detector imaging have demonstrated that high-contrast images of nearby stars do not have the featureless background that would make detection of faint nebulosity or planets easy. The brightness of an Earth at 10 pc is $V=30$ mag. While a visible light measurement of this depth is possible with many orbits of HST observation, it is probably not achievable relatively close to very bright TPF targets. Experience has shown that fields with a high galactic latitude typically contain only one to a few point sources, but may have numerous faint galaxies in the field. STIS fields ($52'' \times 52''$) near ϵ Eri were observed to levels of $V \sim 29$ mag. These fields were found to contain two galaxy clusters. Not all stars of interest for planet searches will be at high galactic latitude; observations of other stars near the galactic plane have backgrounds that are dominated by stars (e.g., HD 163296) but which may still contain one to a few galaxies.

These structured backgrounds will affect both TPF-C and TPF-I. Extended nebulosity (of whatever source) hampers PSF subtraction and spectral deconvolution techniques and may necessitate observations at more spacecraft orientations in order to obtain a clean measure of the PSF (with consequent demands upon instrument stability). TPF-I, especially operating at 10 microns, will be subject to confusion with background dusty galaxies.

One workaround to both of these difficulties will be feasible for some high priority planet search targets which are sufficiently nearby that the star has an appreciable proper motion. Deep conventional or coronagraphic imaging obtainable now in the optical and NIR would facilitate identification of sources that would be in the background at the epoch of TPF observations. The typical proper motion for these stars (>0.1 arcsec/year) means that the nearby targets TPF-C or TPF-I will observe are >1 arcsec away from their future background sources.

Having a complete, deep inventory of such objects would make first-epoch TPF observations more useful, by being able to reject the majority of the sources in the field and focus attention on those with a higher probability of being physically associated with the star of interest. It will also be essential for mission planning purposes, by enabling scheduling that places the star at locations in its proper motion track that have the least background contamination. Knowing the frequency, timing, and duration of such observation windows will provide the data needed for optimal planning of a TPF mission, and it may provide requirements on component lifetimes and reliability.

The brightness of an Earth at 10 pc in the infrared is $0.3 \mu\text{Jy}$ at $10 \mu\text{m}$. Unfortunately, the sensitivity and angular resolution of Spitzer are poorly suited for measuring the background fields for TPF. While Spitzer can reach a noise level of $1 \mu\text{Jy}$ at $8 \mu\text{m}$ in a few hours observing, it will not be able to achieve that level at an angular separation less than an Airy ring ($2.5''$ for Spitzer at $8 \mu\text{m}$) away from sources that are 1 million times brighter! Observations with a ground-based AO system at $2 \mu\text{m}$ may be the most relevant way to characterize TPF fields in the infrared, but it should be recognized that these will fall far short of the desired

sensitivity or angular resolution. Even with a relatively poor temporal baseline (a few years instead of a decade) it will be important to use the 3-, 5-, and 10- μm coronagraphic capabilities on JWST to characterize TPF targets.

5.5 Theory and Modeling of Target Stars

Contamination of the surface layers of host stars

The accretion of residual planetesimals and the consumption of some terrestrial planets contaminate the surface layers of their host stars with metal-rich material. Theoretical analysis of the effects of enhanced opacity in the outer layers, the mixing of the newly added material, and the associated effects on stellar oscillations are important for the inference of terrestrial planet formation in metal-enriched stars with known gaseous giant planetary companions.

Spectral energy distributions of host stars

The physical and chemical properties of the atmospheres of extrasolar planets depend on both the details of their formation and the radiative forcing from the host star. The presence and detectability of planetary atmospheric features will depend on the coupling of atmospheric photochemistry, much of which is driven by the UV flux of the star, and the atmospheric thermal structure, which is an outcome of the spectral energy distribution of the host star throughout the visible and IR. Modeling of the coupled planetary processes of atmospheric chemistry and thermal structure, therefore, requires knowledge of the spectrum of the host star, including any significant absorption or emission features, over the entire wavelength range from the UV to the far-IR. In particular the stellar UV radiation can strongly influence the detectability of ozone, and this effect needs to be understood over a range of possible conditions. The relationship between stellar spectral type, which is based on information gathered in the visible, and the potential range of UV characteristics for stars in that spectral type should also be explored. Differences in UV flux for a given spectral type may have significant impacts on both the likelihood of planetary habitability, and therefore the star's suitability as a TPF target, as well as the relative detectability of biosignatures such as ozone.

5.6 Summary: Opportunities, Risk, and Priorities

To make the most productive selection of TPF target stars, it is crucial to better understand, through observation, synthesis, and theory, the stellar characteristics that favor both habitability and detectability of any encircling planets. Ongoing and future missions relevant to these inquiries are listed in Table 10 (page 60).

Several stellar characteristics are required as input to theoretical planetary models that can assess both habitability and detectability of planetary characteristics based on stellar type. In particular, accurately calibrated full-wavelength-coverage spectra (between different instruments) are needed, as extrasolar planetary atmosphere characteristics are sensitive to the spectral energy distribution from the UV to the far-

Table 10. Ongoing and Future Space-Based Missions Relevant to the Study of Stars That May Harbor Earth-Like Planets

Science Objectives	Timeline	Supporting Facility	Science Program
Observations of Stellar Photospheres for Astrobiology	2004–2010 [†]	HST	UV, optical
	2004–2010	FUSE	UV
	2004–2010	Chandra	X-ray
	2004–2010	XMM	X-ray
Images of Target Fields	2003–2010	HST	ACS, NICMOS images: R=29 mag, 5 σ in 3 hr
	2003–2010	Spitzer	IRAC images: $F_{\nu}(8 \mu\text{m}) \sim 4 \mu\text{Jy}$, 5 σ in 3 hr
	2011–2015	JWST	NIRCAM and MIRI images J>30 mag; $F_{\nu}(8 \mu\text{m}) < 1 \mu\text{Jy}$
Companion Survey	2003–2010	HST	ACS, NICMOS coronagraphic images
	2004–2015	Ground AO	10^{-8} contrast within 0.1–0.5 arcsec radius
	2010–2012	2-m class space-based coronagraph	10^{-9} contrast within 0.3–3.0 arcsec radius

[†] The future timeline for observations with the Hubble Space Telescope, noted here and elsewhere in the text, is speculative.

IR. Several existing space observatories have the capabilities necessary to contribute to this effort, and existing data (such as IUE spectra) are available for a large fraction of TPF candidate stars. However, these data may require recalibration, or supplementation with data from other observatories.

In addition to intrinsic stellar characteristics, it is important to characterize each target's circumstellar environment to assess detectability of planets. Imaging of target fields requires high angular resolution and high dynamic range so that faint background objects can be detected. Since many target stars will have large proper motions, imaging observations with HST done years before TPF-C is launched offer the prospect of identifying objects that may affect TPF, but which will be too close to the target to be separated on images taken at the epoch of TPF-C or TPF-I.

5.7 Assessment of Progress

In future versions of this document, an assessment of progress will be included here.

6 Characteristics of Planets That May Support Life

Relevance to TPF

TPF-C and TPF-I distinguish themselves from similar missions that seek to determine the number of habitable worlds in our Galaxy by striving for direct detection of extrasolar terrestrial planets. Direct detection will allow photometric, spectral, and temporal characterization of the worlds that we find.

TPF-C and TPF-I will emphasize the characterization of habitable worlds, rather than merely “Earth-like” ones. To explore the plausible range of terrestrial planets that we may find, it is important to create self-consistent theoretical models of planetary characteristics and evolution. These models can both inform the instrumentation requirements and search strategies for each TPF mission, and provide a theoretical framework for analysis of the mission data.

Metrics for Decision Making

A major goal of the TPF missions is to provide data to the biologists and atmospheric chemists who will be best able to evaluate observations for evidence of life. At visible and infrared wavelengths, the biomarkers that have been identified include spectral features of molecular oxygen, water, carbon dioxide, ozone, and methane. What spectral bands should be observed and with what spectral resolution in order to provide convincing evidence of life? Recommendations must be made to establish the wavelength band limits for the optical coronagraph and mid-infrared interferometer designs. Recommendations must also be made for the required spectral resolution in each band. Although the report by Des Marais et al. on *Biosignatures and Planetary Properties to be Investigated by the TPF Mission* (Jet Propulsion Laboratory, Pasadena, CA:



Figure 22. Simulated image of a cloud-free, illuminated Earth as seen from the Moon.

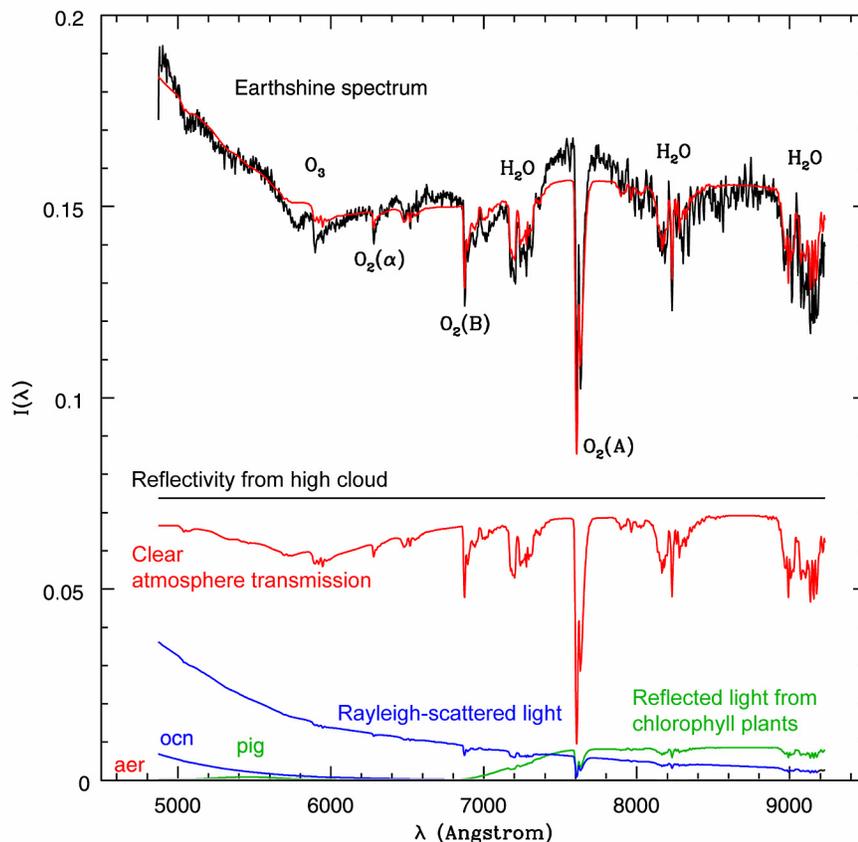


Figure 23. Reflectivity spectrum of Earth, as seen in light reflected from the moon. The observed spectrum is shown at the top, with a model spectrum superimposed. The elements of the model include reflectivity from high clouds, transmission through the clear atmosphere, Rayleigh-scattered light, reflected light from land plants (chlorophyll), and contributions from “ocn” subsurface ocean water, “pig” green-pigmented phytoplankton, and “aer” aerosol scattered light.

JPL Pub 01-008, 2001) made preliminary recommendations for wavelength ranges and spectral features, this work remains to be refined and extended, and will likely be an ongoing subject of debate.

The further development of biomarkers should proceed using a progressively developed set of lists. It is worth noting that both TPF-C and TPF-I will measure global planet properties. This is illustrated by the view of Earth in Fig. 22, and the corresponding integrated spectrum of Earthshine shown in Fig. 23. The lists should therefore be developed with that mind. The lists are described as follows:

1. A quantitative list of conditions necessary and sufficient for life should be developed. Here “life” includes any of the usual Earth-like forms: plants, animals, and bacteria. This list would include items such as temperature, liquid solvent presence, feed gases, abundances of gases, feed trace elements, radiation ranges, solid surface, energy sources, and the presence of an atmosphere.
2. Another quantitative list of signs of life, both necessary and sufficient as well as probable, should be developed. This list would include items such as thermodynamic disequilibrium, product gases, product liquids (if any), solids, reflection spectra, transmission spectra, and emission spectra.

3. A third list of conditions that encourage life should be developed. This list would include items such as weather, climate variations, stress from such variations, plate tectonics, rotation rate of planet, ultraviolet and x-ray fluxes, and mass of atmosphere.

Together these lists, and the considerations that go into generating them, will prove valuable in guiding the type of instruments to be built for TPF, and the philosophy underlying the interpretation of the data that will result from a TPF mission.

Schedule and Deliverables

In Pre-Phase A, a preliminary version of the above three lists is needed prior to the mission concept review. These lists will provide strong guidelines for the wavelength range and spectroscopic resolution needed to detect life in each wavelength regime, and help to assess technological readiness.

In Phase A, these lists need to be developed in more detail to set the parameters of the instrumentation. In particular, this will allow filters and spectrometers to be developed that are suited to the characterization of Earth-like planets.

6.1 Future Observational Programs

Characterizing planets that may support life is, of course, a primary goal for TPF itself. Opportunities to understand the physical and chemical characteristics of planets, as opposed to the properties of their orbits, are probably quite limited prior to TPF-C. The most promising technique, already demonstrated for the case of the giant planet around HD209458, is transmission spectroscopy. The possible use of transmission spectroscopy to study the atmospheres of transiting *terrestrial* planets should be investigated with theoretical studies. Based on these studies, we should seek to retain the relevant bright-object and wavelength capabilities on upcoming premier facilities, notably JWST and the next-generation of 30-m ground-based telescopes. *See also Section 3.2.*

Observations of Earthshine (light from the Earth reflected by the dark side of the Moon), as shown in Fig. 23, can be used as a preliminary test of techniques to characterize the surface and atmospheres of Earth-like planets. Both photometric and spectroscopic data are being obtained at optical and near-infrared wavelengths. Long-term observations will be useful in discerning diurnal, seasonal, and inter-annual variations. Coordination of observations for maximum effect and the development of a public database of Earth-shine observations may prove very useful for the development of instruments, techniques, and observational strategies.

6.2 Theory and Modeling of Habitable Planets

Research Goals

The theoretical modeling research goals are to explore the plausible range of habitable planets and to improve our understanding of the detectable ways in which life modifies a planet on a global scale. Specific activities to address these goals could include:

- Improving our understanding of the origin of planetary systems, and the early history of volatile delivery and loss mechanisms for terrestrial planets of varying size and mass. This research would help us define the potential range of terrestrial planet compositions and the likelihood for habitable worlds.
- Developing comprehensive models of terrestrial planet environments to determine how the evolution of atmospheric composition (including volatile loss) affects climate, as well as surface and interior processes. This research would elucidate how these changes affect habitability over time, and improve our understanding of the extent and evolution of the habitable zone over a star's lifetime, for planets of very different compositional types. This would, in turn, improve TPF's ability to classify a planet as habitable, and therefore be of interest for follow-up observations.
- Using atmospheric, climate and radiative-transfer models to model planetary disk-averaged spectra and understand the range of planetary conditions that can be discriminated from low resolution full-disk spectra at visible, near-IR, and thermal wavelengths. This research would be directly relevant to defining TPF instrument requirements such as wavelength range, spectral resolution, and sensitivity.
- Understanding and modeling a variety of spectral and temporal (diurnally and seasonally varying) biosignatures, both surface and atmospheric, including signatures of ozone, oxygen, and methane. Other potential biosignatures from different metabolisms should also be explored and characterized, including volatile methylated and sulfur compounds. It is also important to understand changes in these signatures over Earth's geological and biological history. What did the early Earth look like before the rise of an oxygen-dominated atmosphere? How would we recognize this for a planet around another star? How will we distinguish between uninhabited, habitable, or inhabited worlds, based on the globally-averaged information that will be obtained by TPF-C and TPF-I?
- Undertaking observational and modeling studies to determine what planetary conditions can give rise to abiotic processes that mimic biosignatures, and determining what ancillary measurements, if any, would be required to separate false from true biosignatures.

With arbitrarily high signal-to-noise and spatial and spectral resolution, it is relatively straightforward to remotely ascertain that Earth is a habitable planet, replete with oceans, a greenhouse atmosphere, global geochemical cycles, and life. The interpretation of measurements with limited signal-to-noise ratio and resolution from other planets will be far more challenging. What constraints can these kinds of observations offer on the presence or absence of an ocean, a greenhouse atmosphere, and various

atmospheric biosignatures? Are there optimal observational strategies (spectral range, observation times) to distinguish between uninhabitable, uninhabited, and life-bearing planets? Geological processes may be capable of producing apparent biosignatures in a planet's atmosphere. Can we discriminate against these false positives based on other information? How common are these situations?

Planetary Characterization and Evolution Models

Since TPF-C and TPF-I will study the global atmospheric properties of planets that they detect, the most relevant evolutionary models to study are those that have direct implications for a planet's atmosphere. In our own Solar System, and especially on Earth, the process of plate tectonics plays a key role, as it is the means by which the surface and mantle interact and cycle volatiles. This process can contribute significantly to planetary habitability by providing one link in the carbonate-silicate weathering cycle, which buffers atmospheric CO₂. Therefore, we should explore the prevalence of plate tectonics as a function of planetary composition and size.

Unfortunately, some of the basic planetary data that we will obtain – such as (current) radius, mass, and albedo – will not provide significant data regarding a planet's formation history. Our own Solar System illustrates the difficulty. Venus and Earth, which are nearly identical in size, mass, density, and volatile abundance, currently look like they should belong to different planetary systems!

Since planetary evolution can be so divergent, it is important to understand the divergent evolutionary paths that terrestrial planets may take, after their formation. Venus, Earth, and Mars provide three examples of “end states” of terrestrial planet evolution, and there are probably many more possible outcomes that should be explored/understood.

The evolution of atmospheres and climates on rocky planets

Evolution of the planetary surface and atmosphere is determined by many factors, including the spectral energy distribution of the host star, the astrophysical environment, the planet's initial volatile inventory, and subsequent geologic activity and biology. Consequently, terrestrial planet evolution needs to be studied as a whole to establish bounds to habitability. Earth's atmosphere has experienced dramatic evolution over 4.5 billion years, and other planets may exhibit similar or greater evolution, and at different rates. Changes in any greenhouse effect and the efficiency of atmospheric circulation will drive climate change and control habitability and bound the habitability of planets with non-Earth-like rotation rates (such as tidally locked planets around M stars) or obliquities (such as Earth-like planets without a Moon or with high rotation rates).

Models of volatile evolution for Earth-like planets could be used to explore the implications of changes in the inventory and distribution of volatiles between the interior, surface, and atmospheres of rocky planets. Calculation of the dynamical transport of volatiles through planetary systems can be carried out for systems whose giant-planet configurations are already known. Water is of special interest here both because of its obvious importance to habitability and because standard nebular models predict its depletion at distances corresponding to the habitable zone.

The Evolution of Earth's Atmosphere

A useful topic for continued study is the evolution of Earth's own atmosphere. We know very well which gases, e.g. O₂ and O₃, represent easily detectable biomarkers in Earth's present atmosphere. However, we are also reasonably sure that, although O₂ and O₃ were virtually absent prior to about 2.3 billion years ago, life itself was present back to at least 3.4–3.5 billion years ago. So, there was at least a billion-year period during which one would have needed to look for other biomarker gases in order to determine from remote sensing that Earth was inhabited. Methane has been suggested as a possible biomarker gas during this period, as it is produced by anaerobic microbes and is also reasonably stable against photolysis. Today, methane is produced mostly biologically but there may also be small abiotic sources as well, such as reactions of warm seawater with Fe- and Mg-rich rocks deep beneath the seafloor. These reactions form serpentine minerals, along with partially oxidized iron in the form of magnetite, Fe₃O₄. As the iron is oxidized from Fe²⁺ to Fe³⁺, dissolved CO₂ in the seawater is reduced to CH₄, which then leaves the mid-ocean ridge system through off-axis hydrothermal vents. We need to better understand modern abiotic methane sources in order to be able to estimate how much methane was produced abiotically in the past. Similarly, we need to develop models of anaerobic ecosystems to estimate what the biological methane flux may have been in the distant past. Without this type of information, it will be difficult to interpret what a positive identification of CH₄ might mean.

However, O₂, O₃, and CH₄ are good biomarker candidates that might be detected by a low-resolution TPF instrument. There are good biogeochemical and thermodynamic reasons for believing that these gases should be ubiquitous byproducts of carbon-based biochemistry, even if the details of alien biochemistry are significantly different than the biochemistry on Earth. Production of O₂ by photosynthesis allows terrestrial plants and photosynthetic bacteria (cyanobacteria) to use abundant H₂O as the electron donor to reduce CO₂, instead of having to rely on scarce supplies of H₂ and H₂S. The advantages of this innovation would presumably apply to alien plants and bacteria as well. O₃ is produced photochemically from O₂, so it carries much the same information about the prevalence of life. O₃ builds up nonlinearly with O₂ abundance, however, so it is a good indication of photosynthetic activity even at O₂ concentrations 100 times smaller than today. CH₄ is expected to be a ubiquitous byproduct of metabolism in anaerobic environments because it is extremely stable thermodynamically. Models of early Earth atmospheres suggest that both CO₂ and H₂ should have been present at reasonable concentrations. Thus, organisms could have made a living from the reaction: $\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$. The thermodynamic energy yield of this reaction would be the same on extrasolar planets, provided that their atmospheres contained similar concentrations of CO₂ and H₂. Hence, there is every reason to believe that alien organisms, if they exist, would also have evolved the capability of generating methane.

However, we should also be cautious about focusing entirely on O₂, O₃, and CH₄. Although these gases appear to be our “best bets” for detecting life remotely, they are each somewhat ambiguous. Like CH₄, O₂ also has abiotic sources that might be important on some types of Earth-like planets. These include a transient source from photolysis of CO₂, followed by recombination of O atoms to form O₂ (O + O + M → O₂ + M), as well as a net source from photolysis of H₂O, followed by escape of hydrogen to space. (The first source is transient because the CO formed from CO₂ photolysis will eventually recombine with oxygen to reform CO₂.) We need to understand the abiotic sources of O₂, so that we can identify when it might constitute a “false positive” for life. We should also explore the question of whether there might be other biogenic trace gases that might accumulate to detectable concentrations in other planetary atmospheres. Currently identified potential candidates include volatile methylated and sulfur compounds. Although it is

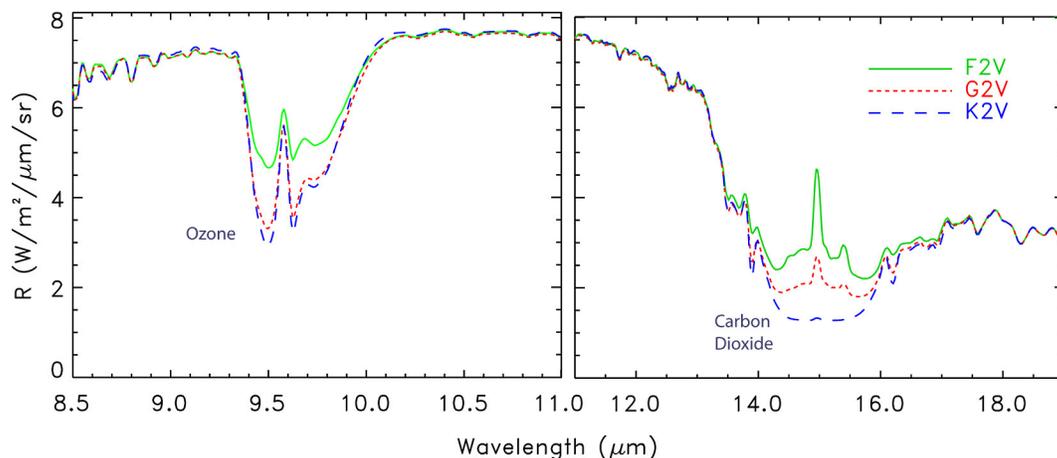


Figure 24. These spectra show the appearance of Earth-like planets orbiting within the habitable zones of stars of F2V, G2V and K2V stellar type. In each case, a weakly-coupled radiative/photochemical atmospheric model was used to determine the equilibrium atmospheric composition and vertical structure for a planet with Earth’s modern atmospheric composition, and radiatively forced by the UV to far-infrared spectrum of a star of each spectral type. A sophisticated radiative transfer model was then used to create a synthetic spectrum of the global spectral appearance of the planet from space, using the equilibrium atmospheric composition as input.

known that these compounds are produced by microbes, it is not yet fully understood how stable (or detectable) these compounds are in atmospheres of different composition and for stars of different spectral type and incident UV flux. These uncertainties, however, could be addressed by further modeling studies. Clearly, if we can expand the potential suite of detectable biogenic trace gases, and understand the condition under which they are most likely to be detectable, we will gain more confidence in our ability to identify life remotely.

Expected Near-term Progress

Weakly coupled photochemical/climate models have already been used to study problems such as the dependence of ozone and trace gas concentrations on atmospheric O_2 level and on stellar type. These models can be improved by incorporating more rigorous radiative transfer techniques, by more tightly coupling the atmospheric physical and chemical processes to produce self-consistent results, and by more realistically incorporating the effects of clouds on the climate and inferred detectability of planetary features. These models will provide the best available assessment of global planetary atmospheric composition, thermal structure, and detectability of atmospheric and surface characteristics of interest. They will also allow the exploration of terrestrial planet types different from those found in our own Solar System. In particular, it is important to develop models of how biogenic trace gas emissions are related to atmospheric constituent levels, such as oxygen.

The results of modeling, illustrated in Fig. 24, show the changes in detectability and shape of spectral features due to ozone, carbon dioxide, and methane for the “same” planet around stars of different spectral type. These observed changes in detectability are due to an interplay between the star’s spectrum, the photochemistry of ozone, and coupled changes in the thermal structure of the planet’s atmosphere. These models were run for host stars of F, G, and K spectral type, but an interesting avenue for future exploration would be to also look at the likelihood of habitability, and the potential detectability of biosignatures such

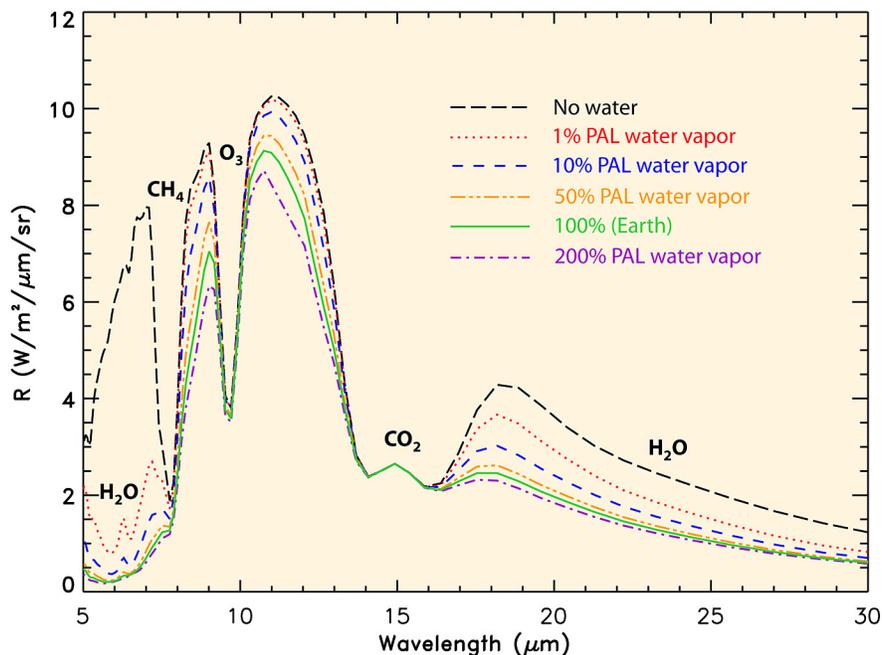


Figure 25. The appearance of Earth-like planets as seen in the mid-infrared wavelength range for a range of different planetary water abundances, shown as percentages of Earth’s present atmospheric level (PAL). These synthetic spectra were generated using a planetary radiative transfer model and convolved to mimic the spectrum seen by a spectrometer with a constant wavenumber resolution of 40 cm^{-1} .

as ozone, for planets around M stars. M stars, being 70% of the nearby stellar population, would be a rich source of potential targets for TPF, but they have several characteristics, including low-level yet highly variable UV flux, that has previously been believed to decrease the likelihood that they harbor habitable planets. A more rigorous modeling exploration of the likely planetary environments for M star hosts would provide valuable input for TPF target star selection by allowing us to make recommendations regarding if, or under what conditions, M stars would make suitable host stars.

Figure 25 shows the modeled appearance of Earth-like planets for different water abundances. The results indicate two potential regions in which to detect water vapor with Spitzer, shortward of $8 \mu\text{m}$, and longward of $18 \mu\text{m}$. The $6.3\text{-}\mu\text{m}$ band is the most sensitive, however, and the easiest to interpret. Without water vapor, the $6\text{--}8\text{-}\mu\text{m}$ region is bright and relatively easy to detect. Note also that when not obscured by abundant water vapor, the $7.7\text{-}\mu\text{m}$ band of CH_4 is relatively easy to detect, even at the low concentrations present in the Earth’s atmosphere (1.6 ppm).

Contributions to TPF Precursor Science

The modeling of planetary systems and terrestrial planets will improve our understanding of the potential range of habitable worlds, while providing the theoretical framework for the analysis and interpretation of TPF data. This research will also allow us to determine which gases, surface spectral features, and time-variable characteristics are potential biosignatures for extrasolar life.

6.3 Summary: Opportunities, Risk, and Priorities

Within the planetary science and Earth observing communities, there is a wealth of existing models and data that can be modified, augmented, or incorporated into planetary formation and volatile delivery models, or in global models of terrestrial planet equilibrium states and evolution. These models, in the service of TPF science, can be used to explore the likely range of characteristics that will be observable for extrasolar terrestrial planets, and they can help us better understand the detectability of these characteristics as a function of planetary composition and age, and the spectrum of the host star.

Advances in the next few years, allowing incorporation of more detailed biogeochemical cycles into planetary models, will allow us to search for biosignatures beyond the current modern-day-Earth-centric spectral suite of ozone, methane, chlorophyll, and leaf reflectivity features. The development of these tools will greatly increase our ability to explore and assess detectability and likelihood issues for specific planetary and life characteristics as our knowledge of this field continues to evolve. Integrated planetary models would also allow us to characterize and understand the global appearance of the Earth throughout its 4.6 Gy of evolution, including the life-supporting Earth prior to the rise of significant amounts of atmospheric oxygen. Continued modeling will also allow us to better identify possible “false positives,” abiotic planetary characteristics that may mimic sought-for biosignatures in planetary spectra. In the short term, continued work to model planetary environments and their appearance to astronomical instrumentation will provide input to requirements for TPF instrumentation characteristics such as sensitivity, spectral resolution, and wavelength range that will work to maximize the likelihood of detecting and being able to characterize habitable and inhabited worlds.

Without these theoretical studies, we risk focusing only on those terrestrial characteristics and biosignatures that are understood via direct observation of the Earth and other terrestrial planets in our own Solar System. However, Earth is potentially only one of many examples of a habitable world, and if we focus and design based only on a search for strictly Earth-like characteristics, we greatly reduce our chance of finding and recognizing other forms of habitable or inhabited worlds.

6.4 Assessment of Progress

In future versions of this document, an assessment of progress will be included here.

7 Development of TPF Precursor Science

The preceding chapters have described the principal themes of TPF precursor science and their relevance to the development of TPF-C and TPF-I. These areas of research are listed on the left-hand side of Fig. 26. For this research to be implemented, resources need to be made available and the research should be coordinated to the greatest benefit of TPF. This chapter describes how that work could be fostered and coordinated. Priorities for TPF precursor science are then presented in Chapter 8.

Support for TPF precursor science is fostered through coordinated programs managed at the Jet Propulsion Laboratory on behalf of NASA Headquarters. The TPF Project devotes 10% of TPF's budget to directly support the scientific community in its vital role in the development of TPF precursor science. This is distributed among numerous activities, with approximately half being specifically directed to the NASA



Figure 26. Summary of the principal TPF precursor science themes and programmatic objectives.

Research Announcement on *TPF Foundation Science*. The range of activities is as follows:

- *TPF Foundation Science* (NASA Research Announcement)
- Michelson Fellowship Program
- TPF Science Working Group
- Coordinated activities with the European Space Agency
- Workshops and conferences
- New science instrumentation (for example, new radial velocity instruments)

All of these activities contribute to growing the community of scientists engaged in TPF-related research. Ongoing funding for TPF precursor science is provided within the TPF Foundation Science NRA. This is particularly important because it provides a mechanism for peer-review and directed funding emphasizing the research within the themes outlined in this document. Young researchers, in the early stages of their career, are provided support through the Michelson Fellowship Program to engage in new science and technology programs related to TPF. A much broader network of scientists is being fostered through coordinated activities with the European Space Agency — most noteworthy among these activities is the TPF/Darwin conference series that annually brings together over 200 scientists from both the United States and Europe. Input and guidance from the scientific community is also provided at the twice-yearly meetings of the TPF Science Working Group. The work of SWG members emphasizes the development of the scientific objectives and priorities for the missions, but also includes more direct participation in reviews of progress with TPF-C and TPF-I.

7.1 TPF Foundation Science

The Terrestrial Planet Finder Foundation Science program is an element of the NASA Research Opportunities in Space and Earth Sciences (ROSES) solicitation. This is an annual NASA Research Announcement (NRA) to the science community for basic research proposals to conduct scientific investigations in support of the Terrestrial Planet Finder. Its scope covers: i) the scientific data and theoretical framework required to define the nature and scope of each TPF mission; ii) the scientific data and theoretical framework required to refine the TPF target lists; and iii) the theoretical background required to plan the missions and to interpret the data obtained.

The Terrestrial Planet Finder Foundation Science NRA covers many of the topics discussed in this document, specifically calling out the following tasks:

- Searches for planets by means of any proven technique (e.g., radial velocity measurements, transits, microlensing, high contrast imaging) around a variety of types of stars, including solar, low and high mass, young, and highly evolved;
- Characterization and theoretical understanding of gas giant planets found around other stars;
- Observational and/or theoretical studies of the composition and dynamics of zodiacal and exozodiacal dust, including evidence for cometary material around stars;

- Theoretical and/or observational investigations of the properties of the early Solar System as it may have related to the formation and evolution of habitable environments;
- Theoretical studies relevant to obtaining a more accurate estimate of the fraction of solar-type stars that may harbor terrestrial planets in the habitable zone, including studies of planet formation and migration scenarios in a variety of environments, as well as investigations of dynamical stability of various orbital configurations;
- Measurement of the properties of potential TPF target stars to assess their suitability for the interpretation of TPF results (note that while a long term program of new observations and theory may be required to determine and/or derive these properties, such activities may be possible only via other NASA programs such as the Spitzer Space Telescope or the Keck Interferometer; however, it is outside the scope of this TPF Foundation Science program to solicit proposals for new observations with these other NASA facilities, proposals for which are solicited through other program announcements); and
- Development of a long-term archive of the key observational data and derived parameters in a manner readily usable by the larger community of interested researchers.

Proposals to this program may also include the development of facilities and/or instrumentation that directly enable the proposed execution of any of proposed activities subject to budgetary constraints.

7.2 Consortia for Research in Planet Formation Theory

A very large effort is being expended in the observational search for new planets. The largest gap in the current framework for the development of TPF precursor science is a coordinated effort towards understanding the formation of planetary systems. This topic is central to the *Origins Roadmap*, but has yet to be organized through a NASA-supported research center.

Center for Planet Formation Theory: An institute developed as a Center for Planet Formation Theory would provide a broad-based, collaborative theoretical effort that would be indispensable in placing the wealth of new TPF Foundation Science into a coherent frame. Integrated projects or research consortia that are directly relevant to the TPF precursor activities should be supported. Exoplanetary science is by nature extremely interdisciplinary, bringing together astrophysics, celestial mechanics, hydrodynamics, and even geological, meteorological, and biological expertise. Appropriate models for TPF-related research centers or consortia include the Center for Star Formation and the various consortia supported through the NASA Astrobiology Institute (NAI). The consortia should be composed of investigators with complementary expertise. They should be composed of a few active leaders with groups of strong and energetic postdoctoral fellows and graduate students (funded through direct grants or through the Michelson program). In addition, it would be ideal to fund two to three groups that would bring together theorists and observers for interaction, collaboration, and workshops. Such centers would advance the field of extrasolar planet research by training a new generation of researchers who would themselves help in understanding the surprises that will certainly be found around the curves in the road map toward TPF.

Expanded Support through NASA Research Announcements: Existing support for relevant theoretical efforts primarily come under the Origins of Solar Systems (OSS), TPF Foundation Science, and Planetary Geophysics and Geology (PGG) programs. These programs have been successful and cost effective so far because they are designed to reach many active individual investigators in the field. But these programs are spread very thin. With limited resources, these programs have been heavily over-subscribed. Programs for individual researchers are essential and funding should be expanded as the field of TPF-related research grows.

Graduate and Postdoctoral Fellowships: Increased support for graduate and postdoctoral fellowship programs should continue through NASA and ESA along the lines of the existing Michelson Fellowship Program, although expanding the scope to create fellowships within a center for planetary formation theory.

7.3 Coordinated Catalogs of Data on TPF Target Stars

Central Catalog of TPF Target Star: As described earlier, each astrophysical property of a star has an influence on the existence and longevity of a circumstellar habitable zone. A particularly important preparatory activity therefore is the systematic compilation of information on nearby stars. Recognizing the importance of this activity, NASA has funded the development of the Stellar Archival and Retrieval System (StARS) through the TPF Foundation Science NRA. This database will draw from the published literature and include many of the stellar characteristics described in Chapter 5. It will furthermore benefit from preliminary databases developed through the TPF Science Working Group. Such a database should be given long-term support to consolidate our knowledge of nearby stars and allow the best possible selection of target stars for TPF-C and TPF-I. This facility will provide a centralized and reliable resource for key information on TPF stars, with similar capabilities that the NASA Extragalactic Database (NED) provides for to extragalactic astronomers. The database should provide a uniform set of observational properties including stellar magnitudes, radial velocities, distances and proper motions, levels of exozodiacal emission, and the results of companion searches. Derived or more controversial properties, such as ages and metallicities should be considered for inclusion with careful consideration of their reliability and associated uncertainties. Europe's SIMBAD, the invaluable Encyclopédie des Planètes Extrasolaires, and the nascent NStars program represent good starts, but no service with exactly the right combination of depth and breadth has yet been properly developed.

Support for TPF-Related Databases: Another aspect of NASA's support for precursor activities should include archives of relevant datasets. NASA's recently announced intention of archiving HIRES data from the Keck telescopes is an excellent first step in this direction. The long-term nature of radial velocity and astrometric searches for planets demands careful curation of data so that astronomers can apply a variety of algorithms or combine multiple datasets to improve the estimation of parameters or set more stringent limits. Similar arguments may apply to other NASA supported data sets, e.g., non-Keck radial velocity studies and ground-based transit or microlensing searches.

These databases, services, and archives should be put into place expeditiously to support and to take advantage of TPF-related research with Spitzer, Keck-I, LBT-I, and SIM.

7.4 New Technology for Precursor Science

New instruments for ground-based telescopes offer both new capabilities and can serve as real-world testbeds for technologies relevant to future space missions, particularly TPF-C and TPF-I. Instruments previously and presently being funded by NASA in this category include:

- Nulling interferometer for the Large Binocular Telescope
- Radial velocity spectrometer for new Lick 2-m telescope
- Coronagraph for the Gemini South telescope (the Near Infrared Coronagraphic Imager, NICI)

Additional instruments types one might consider in a program to support TPF include:

- Nulling testbed on a large telescope that could demonstrate a variety of the nulling configurations under consideration for TPF-I.
- Advanced adaptive optics coronagraphs to demonstrate new techniques for wavefront control, diffraction suppression, and point-spread function subtraction.
- Camera to demonstrate interferometric imaging on a telescope like the LBT.

These should be solicited through a NASA research opportunity. The selection process would be the responsibility of the NASA Program Scientist after consultation with the TPF Project. Typical instrument costs will range from \$1–5M with construction times extending over 2–3 years.

The observing programs for any instruments NASA chooses to fund should be closely monitored to ensure that they are providing TPF-critical information in a timely manner as well as providing observing opportunities to the entire research community.

8 Priorities and Recommendations

In this chapter, we summarize the recommendations for TPF precursor science, which are explained in detail in the previous chapters. Precursor science topics differ widely in their contributions to TPF, and they differ in when their contributions are needed. We organize the topics according to priority, for their impact at different phases of development. It is important to emphasize that this prioritization does *not* reflect any attempt to rank the *intrinsic scientific merit* of any of the research topics presented in this document. Instead, this prioritization is derived solely from the relative importance of scientific results in so far as they contribute to the various technical, scientific, and programmatic decisions during the different phases of the development of TPF-C and TPF-I.

Most of the activities described in these recommendations will require funding through sources over which the TPF Project acknowledges it has no direct control. The priorities, timetable, sources of funding, and overall recommendations for this work are described in the following sections.

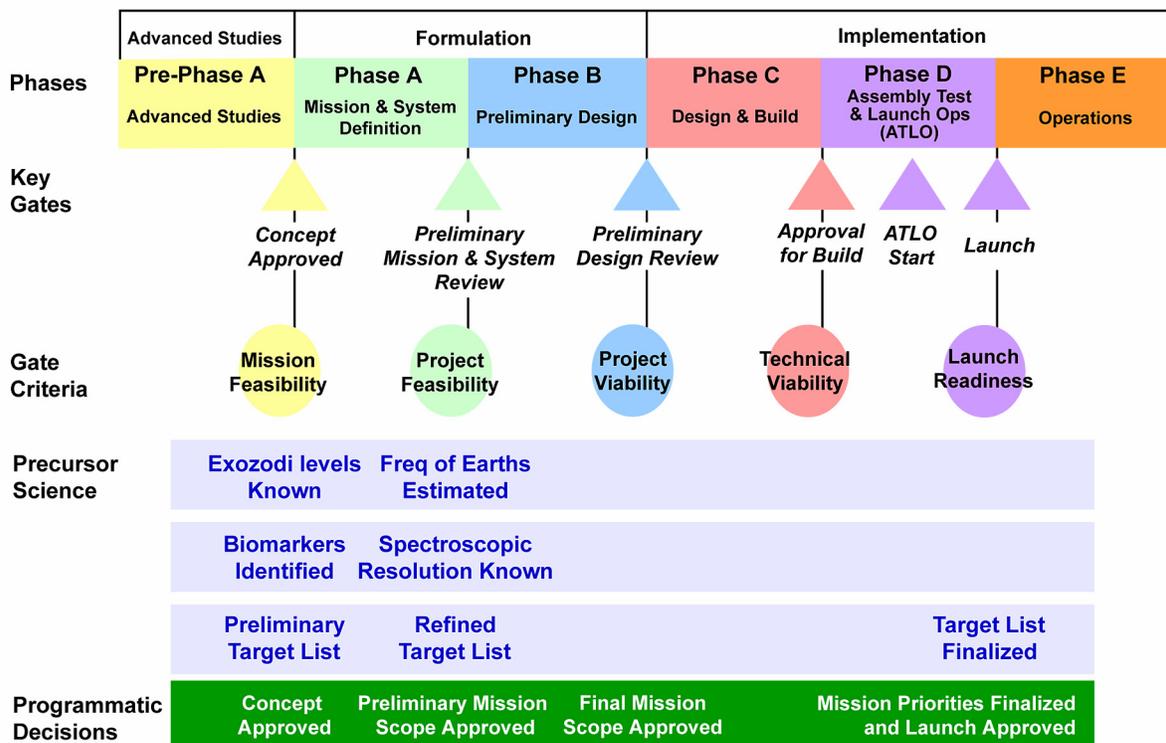


Figure 27. Summary schedule identifying the mission phases and science gates for the Terrestrial Planet Finder.

8.1 Schedule for Prioritized Precursor Science

The nature of fundamental research, in any field, obviously precludes adherence to a fixed schedule. However, in observational astronomy, fundamentally new capabilities, or the enhancement of existing capabilities by a significant factor, almost always result in new discoveries. While some of these discoveries can be predicted, very often, new questions are raised, which require a change in direction, or at least emphasis, in future research. Instead of providing specific dates, we indicate how TPF precursor science is coupled to the phases of TPF development. Specific dates will be set after all the relevant programmatic, technical, and fiscal considerations have been applied. In previous chapters, we have shown the dates when various instruments and missions are expected to yield data or results of importance to TPF. Dates are, of course, always subject to change, but the scientific objectives of planned telescopes and instruments are less uncertain; a slip in the deployment of a new instrument typically results in science *deferred*, not science lost.

In Figure 27, we show a notional timeline for a TPF mission, highlighting the major project phases and gate reviews. TPF-C and TPF-I must pass through the same programmatic gates, and so their project lifecycles can be illustrated by the same timeline. However, it should be kept in mind that TPF-C is scheduled to pass through each of the gates four or five years prior to TPF-I. In green, we indicate the most significant programmatic decisions that each mission must face:

- The approval of the mission concept, coupled to the transition into Phase A.
- The decision of the overall scientific scope of the mission, staged as a preliminary mission scope decision at the entry of Phase B, followed by the final mission scope decision at the entry to Phase C.. The mission scope includes critical parameters, such as the size of the optics, the angular resolution, the sensitivity to faint planet, the mission duration, and the ability to perform moderate-resolution spectroscopy.
- Launch approval.

Figure 27 also shows the major science questions that must be answered to pass through each of the major gates:

- For Phase A: knowledge of the level of exozodiacal emission in the target systems; the number of systems to be searched; and the desired biomarkers to be studied. All are needed for an informed mission concept review.
- For Phase B: the characteristics of extrasolar planetary systems are now the most important scientific inputs to the project. Specifying the needed spectral resolution and selecting a preliminary target list, are also important. Taken together, they define the capability and scientific scope of the mission, which is needed during the preliminary design (Phase B).
- During the period leading up to launch, finalizing and prioritizing the target list becomes the most important science priority because it will greatly influence the ultimate success of the mission.

8.2 Priorities for Project Pre-Phase A

The following is a priority ordering of the precursor science topics which should be pursued from now through the end of the Pre-Phase A period of the project. For reference, the changes in priorities from Pre-Phase A to Phase A are shown in Table 11.

Priority 1: Exozodiacal Dust and the Search for Planets

A survey of all TPF targets for dust on all orbital scales, from <1 AU out to 100 AU, is important for both the mission concept review and selection of preliminary targets. Although selected stars may be studied through individual peer-reviewed proposals, a program coordinated between NASA and ESA is needed that will make the best use of missions such as Spitzer and Herschel.

The TPF and Darwin Projects should also work to coordinate and make best use of upcoming ground-based facilities, such as the nulling instruments at Keck-I and LBT-I in the Northern Hemisphere and the VLTI in the Southern Hemisphere.

Our understanding of levels of exozodiacal dust and its relation to the search for planets would be further bolstered by strong support for a wide-ranging program of theory and modeling.

Priority 2: Characteristics of Extrasolar Planetary Systems

Improved knowledge of extrasolar planetary systems will allow us to predict with greater certainty the scientific return from TPF-C and TPF-I. This question has highest priority once each mission enters Phase A, and therefore should have a high priority in the preceding years.

A comprehensive theoretical investigation into many aspects of the formation and evolution of planets and planetary systems must provide the framework within which to understand necessarily incomplete observational results. The combination of the existing and near-term radial velocity and transit programs — with theoretical insights into the orbital stability of planets, planetary migration, and the relationship between gas giants and rocky planets — will further enrich our understanding of extrasolar planetary systems.

Our current understanding of the frequency of Earth-like planets is based on observations of higher-mass planets discovered through radial-velocity surveys. These highly successful programs should be further supported and encouraged as new detections of lower-mass and longer-period planets continue to refine our estimate of the frequency of Earths.

Radial-velocity surveys would be better supported through the development of new specialized high-resolution échelle spectrometers to offset the current demand for these instruments. Investments in new equipment for radial velocity surveys, directed also at under-utilized 2–3-m class telescopes, would represent an excellent strategy in the development of workhorse instruments for extrasolar planet detection.

Ground-based transit surveys that precede the space-based Kepler mission should also be encouraged. Of special interest is the development of a world-wide network of dedicated wide-field transit or microlensing search telescopes that would allow follow-up studies of bright targets.

This investment in new survey equipment could be further leveraged if robotic observations were promoted at remote sites with excellent seeing conditions.

Priority 3: Characteristics of Stars That May Harbor Earth-Like Planets

The TPF project needs to determine which stellar parameters are most relevant to the search for life. These parameters, once known, will need to be monitored over time for the stars included in the target list. Spectroscopic observations over a broad range of wavelengths will be needed with coordinated access to appropriate space observatories run by NASA and ESA. The TPF and Darwin Projects should work with NASA and ESA to ensure a coordinated observing program to observe TPF target stars.

The study of background fields of many target stars should be monitored in the years prior to TPF-C and TPF-I. Since many target stars will have large proper motions, imaging observations with HST done years in advance offer the prospect of identifying objects which may affect TPF observations, but which will be too close to the target to be separated on images taken at the epoch of either TPF-C or TPF-I.

To complement the studies of nearby stars and potential TPF targets, adequate support is needed for the development and maintenance of comprehensive databases and archives relevant to planet searches. A database, or central clearing-house, with active solicitations to provide missing information (colors, radial velocities, photometric variability, metallicities, binarity, interferometric measurements of diameters, etc.) should be established in Pre-Phase A.

Table 11. Priorities of TPF Precursor Science during Pre-Phase A and Phase A

Priority	Pre-Phase A	Phase A
1	Exozodiacal Dust and the Search for Planets	Characteristics of Extrasolar Planetary Systems
2	Characteristics of Extrasolar Planetary Systems	Characteristics of Stars That May Harbor Earth-Like Planets
3	Characteristics of Stars That May Harbor Earth-Like Planets.	Characteristics of Planets That May Support Life
4	Characteristics of Planets That May Support Life	Exozodiacal Dust and the Search for Planets

Priority 4: Characteristics of Planets That May Support Life

TPF seeks to determine the number of habitable worlds in our solar neighborhood by direct detection of extrasolar terrestrial planets. Direct detection allows photometric, spectral, and temporal characterization of the worlds that we find. TPF will emphasize the characterization of habitable worlds, rather than merely “Earth-like” ones.

To explore the plausible range of terrestrial planets that we may find, it is important to create self-consistent theoretical models of planetary characteristics and evolution. These models will help to refine the instrumentation requirements and search strategies for the TPF missions, and they will ultimately provide a theoretical framework for analysis of the mission data.

8.3 Priorities for Project Phase A

During Phase A, with the fundamental architecture of a mission decided, the critical scientific inputs to the project are those that define the scientific scope. These set how ambitious the instrument must be (mirror diameter or baseline length, collecting area, mass, etc.) and also the scope of the mission — for instance mission duration (which in turn depends on the instrument sensitivity).

Priority 1: Characteristics of Extrasolar Planetary Systems

Improved knowledge of extrasolar planetary systems will allow the TPF Project to confidently reassess the TPF-C and TPF-I prior to their entering Phase B. By the time of the Phase B gates, the capability of the missions will need to be established and the major trades balancing the technological concerns will have to be made.

Priority 2: Characteristics of Stars That May Harbor Earth-Like Planets

The refined target list, to be developed for each mission during its Phase A, will assist in developing the trades (taking into account the expected performance limits) that will ultimately define the capability of TPF. The number of attainable target stars of different spectral types, their distance, and detailed characteristics will largely determine the scientific return of each mission. This target list is more than just an output from a catalog search. As explained in Chapter 5, there are many characteristics of stars that must be measured, and then carefully weighed in importance, before such a refined list can be constructed.

Priority 3: Characteristics of Planets That May Support Life

The spectroscopic resolution is another key parameter that defines the scientific scope. Because the planet signals are very faint, the spectroscopic resolution translates very directly into a sensitivity requirement.

How long does it take to perform spectroscopic follow-up of a significant number of detected planets? The resolution needed is, of course, a question that must be answered using our best understanding of the geophysical, atmospheric, and astrobiological processes that may be present on planets that TPF detects. The details of the studies needed are laid out in Chapter 6.

Priority 4: Exozodiacal Dust and the Search for Planets

Observations to characterize exozodiacal dust will continue to be important during Phase A and also in the Phases through until launch. Activities in this science theme will contribute to characterizing the stars in the list of TPF targets.

8.4 Ancillary Precursor Science

Advances in a broad range of other TPF science is important for developing a coherent theoretical understanding of the formation, dynamics, evolution, and statistics of planetary systems over a wide range of physical conditions. It will also assist in providing a sound framework for interpreting the observational results already made and those that may be expected over the next several years.

A robust program of research and analysis should be supported to advance the field of planet finding over a broad front. Although each individual project may not be critical for TPF, a larger ensemble of activities will enrich the TPF program and train a cadre of scientists ready to undertake future challenges of TPF-C and TPF-I. The following activities serve as examples of possible topics in ancillary precursor science:

1. Observations of protoplanetary disks and young stellar objects with ground-based adaptive optics or space-based coronagraphy.
2. Planet and brown dwarf searches targeted at stars of earlier and later spectral types than are likely to be amongst the core targets for TPF.
3. Theory and modeling of habitable planets in unusual environments, such as around close binary or multiple stars, or as satellites of gas-giant planets.
4. Simulations and models of the dynamics of planetary interiors and how the dynamics affect the habitability of terrestrial-type planets.

No prioritization of ancillary science programs is listed or included here. Indeed, much of the importance of the diverse research into extrasolar planets derives from its interdisciplinary nature, therefore prioritization is not particularly meaningful. Such science activities are only ranked, collectively, as lower priority because they are tangential to the themes described in previous chapters. Describing these activities as *ancillary* does not imply they are of any less intrinsic scientific importance. Rather, it reflects the fact that they are less critical for decisions that the TPF Project must make during the life-cycle of the missions.

Table 12. Contributions of Instruments and Missions to TPF Precursor Science

Instrument / Mission	Science Contribution	Programmatic Gate for TPF-C	Science Theme
Activities During Pre-Phase A <i>Emphasis on Mission Concept Review</i>			
Spitzer	IRS/MIPS survey of ~250 stars	Phase A	Exozodi
Radial velocity monitoring	Saturn mass planets at several AU	Phase B	Planetary Systems
COROT/MOST	Transits of planets	Phase B	Planetary Systems
Keck-I, LBT-I, VLT-I	Dust in habitable zone (10 μm) for ~ 150 stars	Phase A	Exozodi
Theory/modeling	Estimate of frequency of Earth-like planets	Phase B	Planetary Sys.
Theory/modeling	Define spectral signatures to be searched	Phase A	Biomarkers
Activities During Phase A <i>Emphasis on Scientific Scope of the Mission</i>			
Kepler	Statistics of Earth-like planets (transiting)	Phase B	Planetary Systems
Herschel	Images of bright dust disks	Phase B	Exozodi, Target List
Hubble Space Telescope/ACS	Coronagraphy of debris disks	Phase B	Exozodi, Target List
Ground based transit surveys	Statistics of Jupiter-mass to sub-stellar companions	Phase B	Planetary Systems
Ground-based microlensing	Detection of planets in few-AU orbits	Phase B	Planetary Systems
Ground & Space-based Imaging	Statistics of young gas giants, 5–100 AU	Phase B	Planetary Systems
Activities Spanning Pre-Phase A to Phase E (Launch) <i>Emphasis on Development of Target List</i>			
SIM	Masses of few-Earth-mass planets for nearby stars	—	Target List
JWST/HST	Images of TPF target fields $J > 30$ mag; $F_{\nu}(8 \mu\text{m}) < 1 \mu\text{Jy}$	—	Target List
Theory/modeling	Updated estimate of frequency of Earth-like planets	—	Planetary Systems
Ground & Space-based Imaging	Statistics of gas giant planets, 1–10 AU	—	Planetary Systems
Keck-I astrometry	Long-period planets	—	Target List
Stellar characterization and database	Properties of potential targets	—	Biomarkers

8.5 Contributions of Instruments and Missions

Table 12 summarizes how the various missions and instruments contribute to TPF. It is divided into three major sections, as explained in the introduction to this chapter:

- Mission concept review (entry into project Phase A)
- Scientific scope (entry into project Phase B)
- Target list development (all project phases)

This list shows the major instruments and missions (both ground and space based) that contribute to TPF precursor science. A timeline of the missions is also shown in Fig. 28 (page 86). Many of the instruments contribute in more than one area, and their importance could change in the light of new discoveries during the years leading up to the launch of TPF-C and TPF-I. Table 12 represents a snapshot in time of our understanding of the field in mid-2004.

8.6 Budget Recommendations

8.6.1 Recommended Funding Sources

The following budget recommendations are intended to provide an indication of the resources needed to accomplish the objectives TPF precursor science. Although funding for most aspects of this research are beyond the direct control of the TPF Project, the questions that need to be addressed are forefront research activities likely to be allocated time and supported through NASA and other funding agencies such as ESA and the National Science Foundation. We distinguish two distinct classes of funding within NASA to support this work: science support through large missions and support through NASA Research Announcements (NRAs).

Science support through large missions

Many of the observational programs that have been identified will be carried out through facilities already funded separately by NASA. We assume that the large missions e.g., HST, Spitzer, Kepler, SIM, JWST, have their own support for science, and that TPF investigators using those facilities will compete for time and be supported through peer-reviewed proposals.

A key recommendation of this document is, therefore, that key research that supports TPF precursor science should be explicitly recognized and supported within the peer-review process for access to observing time with large missions. Each of NASA's large astrophysics missions should commit to supporting TPF-related research for which the proposer has demonstrated a strong scientific need.

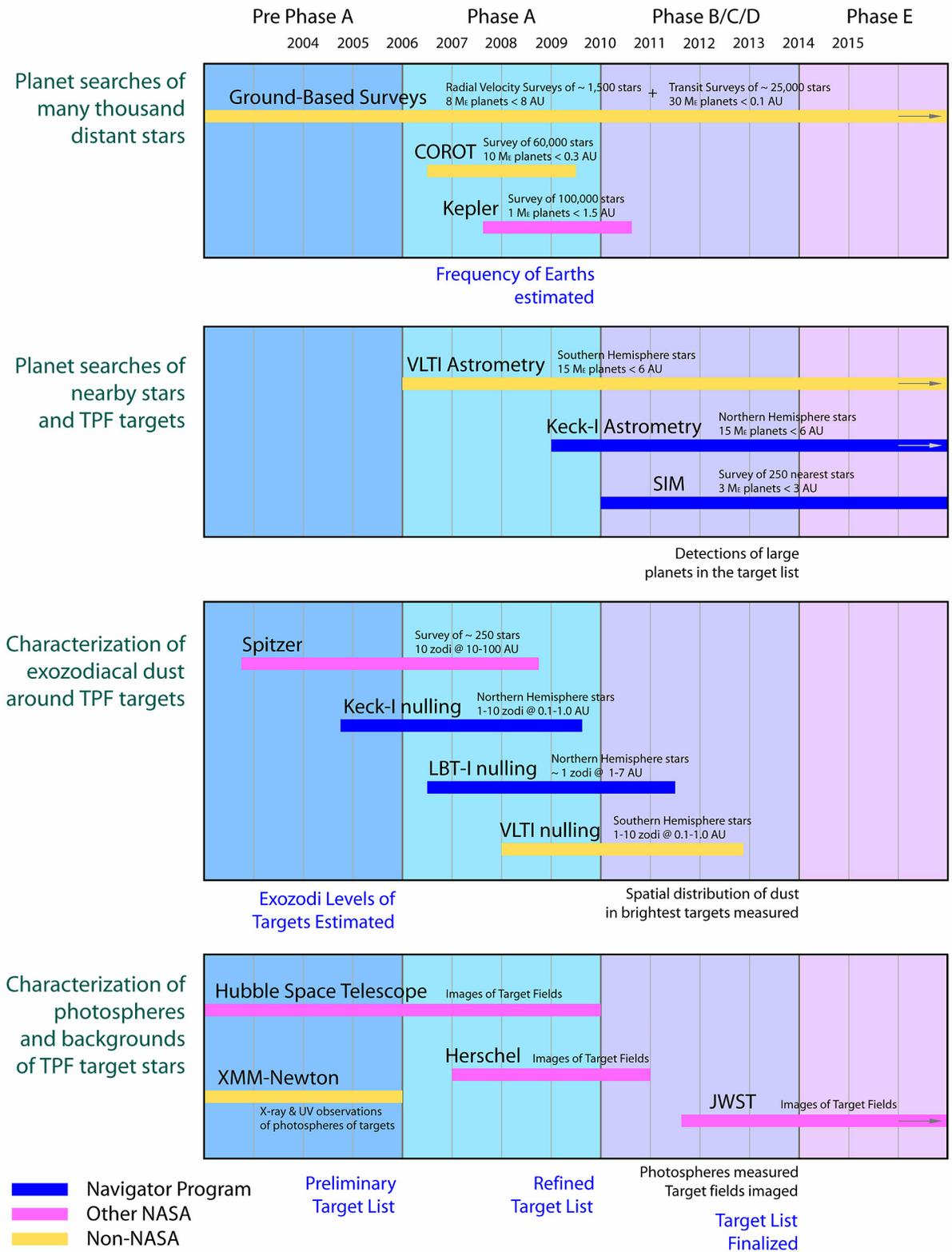


Figure 28. Timeline of missions contributing to the Terrestrial Planet Finder. For reference, the project life-cycle phases of TPF-C are shown color coded in the background.

Support through NASA Research Announcements

Many of the research activities described here naturally fall within the scope of NASA Research Announcements as part of NASA's Research Opportunities in Space and Earth Sciences (ROSES). The research announcements most closely related to TPF are as follows:

1. **Astrophysics Data Program (ADP):** Research involving NASA space astrophysics data that are currently archived in the public domain.
2. **Exobiology (EXB):** Research to understand the origin, evolution, and distribution of life in the universe, including the pathways and processes leading from the origin of a planet to the origin of life.
3. **Long-Term Space Astrophysics (LTSA):** Long-term support, up to a maximum of five years, to enable investigations of appropriately large scope that are substantial and cohesive. This includes topics related to main sequence stars and the formation of protoplanetary disks and debris disks.
4. **Origins of Solar Systems (OSS):** Research related to (a) the formation and early evolution of planetary systems, (b) fundamental research and analysis necessary to detect and characterize other planetary systems, and (c) definition of the scientific performance of possible future space missions that would perform spectroscopy of extrasolar planets.
5. **Planetary Atmospheres (PATM):** Scientific investigations that contribute to the understanding of the origins and evolution of the atmospheres of planets and their satellites, and of comets. The characterization of atmospheres of extrasolar planets is included in the scope of this activity.
6. **Astronomy and Physics Research and Analysis (APRA):** Basic research related to investigations relevant to NASA's programs in astronomy and astrophysics: (a) develop detectors that may be proposed as candidate experiments on future space flight opportunities, (b) science investigations whose completion requires the flight of instruments as payloads on suborbital sounding rockets, stratospheric balloons, or longer duration flight opportunities, (c) develop supporting technology, laboratory research, and/or conduct ground-based observations directly applicable to space astrophysics missions.
7. **Terrestrial Planet Finder / Foundation Science (TPF/FS):** Investigations that provide (a) scientific data and the theoretical framework required to define the nature and scope of the TPF missions, (b) the scientific data and theoretical framework required to define the target lists, and (c) the theoretical background required to plan the missions and interpret the data obtained.

Further information on NASA research opportunities through the Office of Space Science can be found at http://research.hq.nasa.gov/code_s/code_s.cfm.

8.6.2 Recommended Funding Levels

The many diverse areas of scientific research described in these pages are all worthy of pursuit and are worthy to compete for funding support from NASA. Such a large and growing field could easily overwhelm any reasonable research budget. We recommend an overall funding level of approximately \$5 M per year will be needed, in addition to the large mission support described above. This will allow progress to be made in all of the major areas of TPF precursor science. While the recommendations of this document are prioritized from the perspective of TPF with its needs as a NASA project, we expect that the intrinsic scientific merit of every proposal will continue to be foremost in the peer-reviewed selection of proposals for funding.

Only one of the NASA funding opportunities listed above is directly funded by the TPF Project: the *Terrestrial Planet Finder / Foundation Science (TPF/FS) NRA*. The TPF Project recognizes the importance of the *Foundation Science* NRA, by allocating about \$2M of TPF funds per year to it. *Foundation Science* is supported only through TPF Project funds, and all selected awards are directed towards the scientific needs of TPF. An important function of this document will be to serve as a guide to the scope of future Foundation Science proposal announcements.

Additional funds, competed for through the ROSES NASA Research Announcement, will make up the balance of the budget.

8.6.3 Conclusions

Active funding support for TPF, as discussed above, should be maintained throughout the years leading to launch. It is vitally important that the development of TPF-C and TPF-I, and their operation as scientific observatories, be guided at all times by the best scientific consensus understanding of the field of extrasolar planet research. This is especially important, of course, when TPF-C and TPF are actually observing, but making the best use of available knowledge is important at all times. This represents one of the larger programmatic challenges that TPF must face, given its very long development period. We can expect great scientific advances during these years, and we expect, and should demand, that the Project appropriately factor this new knowledge into its development. Helping to begin that process of adaptation is one of the main objectives of *Precursor Science for the Terrestrial Planet Finder*.

Appendices

Appendix A

Contributors

Precursor Science for the Terrestrial Planet Finder has been put together through the efforts of many astronomers, planetary scientists, technologists, engineers, and spacecraft builders. All share the same vision: to advance the state of human knowledge toward the answer to the important questions “Where did we come from?” and “Are we alone?”

This document began in early 2003 through the efforts of Doug Lin and Ted von Hippel on behalf of the TPF Science Working Group, listed in Table 13 (page 92). The initial text has been extensively revised and expanded through the efforts of numerous other contributors. The TPF Project is grateful to acknowledge contributions from Chris Lindensmith (JPL), Richard Key (JPL), Debra Fischer (University of California Berkeley), Margaret Turnbull (University of Arizona), Francis Nimo (University of California, Los Angeles), Giovanna Tinetti (California Institute of Technology), Sean Urban (U.S. Naval Observatory), William Hartkopf (US Naval Observatory), Brian Mason (U.S. Naval Observatory), Karl Stapelfeldt (JPL), Carol Grady (GSFC), David Charbonneau (California Institute of Technology), Dimitar Sasselov (Smithsonian Astrophysical Observatory), and Stuart Shaklan (JPL). The Project is also grateful to acknowledge the assistance of Roger Carlson at JPL Publications.

The TPF Project is also pleased to acknowledge the constructive criticism and support of the Independent Review Team (IRT) chaired by Vernon Weyers, and in particular feedback from its Roadmap Advisory Group (RAG) chaired by Alan Boss. Members of the RAG included IRT members Alan Boss (Carnegie Institution of Washington), Peter Nisenson (Smithsonian Astrophysical Observatory), Vickie Parsons (NASA Langley Research Center), Joseph Wampler (consultant), and Vernon Weyers (consultant), with the addition of John Chambers (NASA Ames Research Center), George Gatewood (University of Pittsburgh), Ron Gilliland (Space Telescope Science Institute), and William Cochran (University of Texas, Austin).

Table 13. TPF Science Working Group

Name	Institution
Charles Beichman (Chair)	California Institute of Technology
Dana Backman	Franklin and Marshall College
Robert Brown	Space Telescope Science Institute
Christopher Burrows	Consultant
William Danchi	NASA Goddard Space Flight Center
Alan Dressler	Carnegie Institution
Malcolm Fridlund [†]	ESA/ESTEC
Eric Gaidos	University of Hawaii at Manoa
Philip Hinz	University of Arizona
Kenneth Johnston	US Naval Observatory
Marc Kuchner	Smithsonian Astrophysical Observatory
Doug Lin	University of California, Santa Cruz
René Liseau [†]	Stockholm Observatory
Jonathan Lunine	University of Arizona
Victoria Meadows	Jet Propulsion Laboratory
Gary Melnick	Smithsonian Astrophysical Observatory
Bertrand Mennesson	Jet Propulsion Laboratory
David Miller	Massachusetts Institute of Technology
Charley Noecker	Ball Aerospace and Technologies Corp.
Huib Rottgering [†]	Leiden Observatory
Sara Seager	Carnegie Institution of Washington
Eugene Serabyn	Jet Propulsion Laboratory
William Sparks	Space Telescope Science Institute
Wesley Traub	Smithsonian Astrophysical Observatory
John Trauger	Jet Propulsion Laboratory
Ted von Hippel	University of Texas, Austin
Neville Woolf	University of Arizona

[†]Members of ESA’s Terrestrial Exoplanet Scientific Advisory Committee

Appendix B

TPF Proposals Funded in 2003

Table 14 (page 94) lists the proposals that were funded in 2003 for TPF Foundation Science (NRA-03-OSS-01-TPF). The table shows the breakdown of topics, as described in this document. The name of the Principal Investigator (PI), the institution, and proposal title are listed.

As noted in the NASA Research Announcement, several proposals submitted to the Origins of Solar Systems Program (NRA-03-OSS-01-OSS) were judged relevant to the TPF program. These investigations are listed in Table 15 (page 95). The complete listing of these NRA winners, which includes abstracts describing the work, is available at the website of NASA Research Opportunities in Space Science:

TPF Foundation Science

http://research.hq.nasa.gov/code_s/nra/current/nra-03-oss-01-tpf/winners.html

Origins of Solar Systems

http://research.hq.nasa.gov/code_s/nra/current/nra-03-oss-01-sso/winners.html

Table 14. TPF Foundation Science Proposals Funded in 2003

PI	Institution	Proposal Title
Characteristics of Extrasolar Planetary Systems		
Fred Adams	University of Michigan	Estimating the Fraction of Solar Systems with Habitable Planets: Effects of Companions on Dynamical Stability and Formation
John Chambers	Carnegie Institution of Washington	Terrestrial Planet Formation around Nearby Stars
William Cochran	University of Texas at Austin	Determination of eta-Earth from Ground-Based RV Observations of M Stars
Gregory Laughlin	University of California, Santa Cruz	A Consortium-based Theoretical Evaluation of the Frequency of Habitable Planets
Harold Levison	Southwest Research Institute	Extra-Solar Terrestrial Planet Formation
John Monnier	University of Michigan	Detecting and Characterizing "Hot Jupiters" with Optical Interferometry: Differential Phase and Precision Closure Phases
Robert Noyes	Smithsonian Astrophysical Observatory	Spreading the Net: A Network of Small Automated Telescopes for Detecting Transiting Extrasolar Planets
Stuart Weidenschilling	Planetary Science Institute	Accretion of Terrestrial Planets in Extrasolar Planetary Systems
Harold Yorke	Jet Propulsion Laboratory	Formation and Evolution of Planetary Systems: Predicting the Frequency of Earth-like Planets Around Nearby Stars
Exozodiacal Dust and the Search for Planets		
Philip Hinz	University of Arizona	High-Dynamic Range Thermal Infrared Surveys for Zodiacal Disks and Giant Planets Around TPF-candidate Stars
Characteristics of Stars that May Harbor Earth-like Planets		
John Stauffer	SIRTF Science Center	StARS -- The Stellar Archival and Retrieval System for TPF Foundation Science
Karen Willacy	Jet Propulsion Laboratory	Prebiotic Chemistry in Planet-Forming Regions
Characteristics of Planets that May Support Life		
James Cho	Carnegie Institution of Washington	The Global Surface Temperature and Cloud Cover of Extrasolar Terrestrial Planets: Implications for Habitability and Detectability
Martin Cohen	University of California, Berkeley	Absolute FUV-FIR Spectral Energy Distributions: a Tool for Selecting TPF Target Stars and Sharper Criteria for Habitability
Eric Gaidos	University of Hawaii at Manoa	Observable Signatures of Extreme Seasonality on Earth-like Planets with High Orbital Eccentricity or Obliquity
Thomas Hearty	Jet Propulsion Laboratory	Whole Earth Spectra with the Atmospheric Infrared Sounder

Table 15. Origins of Solar Systems Proposals Relevant to TPF Funded in 2003

PI	Institution	Proposal Title
Characteristics of Extrasolar Planetary Systems		
Darren DePoy	Ohio State University	Planet Search from High Magnification Microlensing Events
Darren DePoy	Ohio State University	KELT All-Northern Sky Transit Survey: A Survey of Bright Stars for Transiting Planets
Shrivinas Kulkarni	California Institute of Technology	Extrasolar Planets in Binary Stellar Systems
Gregory Laughlin	University of California, Santa Cruz	Detection of Intermediate-period Transiting Planets Through the Coordination of Follow-up Observations of Known Doppler-wobble Planet-bearing Stars
Steven Saar	Harvard-Smithsonian Center for Astrophysics	Improving Doppler Searches for Exoplanets by Reducing Activity-related Radial Velocity Noise
Guillermo Torres	Smithsonian Astrophysical Observatory	Spectroscopic Follow-up of OGLE Candidate Transiting Extrasolar Planets
Exozodiacal Dust and the Search for Planets		
Alice Quillen	University of Rochester	Detection of Outer Extra Solar Planets and Characterization of Disk Properties from Circumstellar Gas and Dust Morphology
Ancillary Precursor Science		
Travis Barman	Wichita State University	Modelling the Global Atmospheric Properties and Phase Dependent Spectroscopy of Extrasolar Giant Planets

Appendix C

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Appendix D

Acronyms

AAT	Anglo-Australian Observatory
ACS	Advanced Camera for Surveys
ADONIS	ADaptive Optics Near Infrared System
ALMA	Atacama Large Millimeter Array
AO	Adaptive Optics
ASO	Astronomical Search for Origins
ASP	Arizona Search for Planets
ATLO	Assembly, Test, and Launch Operations
AU	Astronomical Unit
BEST	Berlin Exoplanet Search Telescope
CfA	Harvard–Smithsonian Center for Astrophysics
CCD	Charge-Coupled Device
CHZ	Continuously Habitable Zone
CMOS	Complementary Metal Oxide Silicon
CNES	Centre National d’Etudes Spatiales
COROT	Convection Rotation and planetary Transits
CSA	Canadian Space Agency
Decl	Declination
EROS	Expérience pour la Recherche d’Objets Sombres
ESA	European Space Agency
ESO	European Southern Observatory
ESTEC	European Space Research & Technology Centre
ExNPS	Exploration of Neighboring Planetary Systems
FFI	Formation Flying Interferometer
FGS	Fine Guidance Sensor
FOV	Field of View
FUSE	Far Ultraviolet Spectroscopic Explorer
GENIE	Ground-based European Nulling Interferometer Experiment
GEST	Galactic Exoplanet Survey Telescope
GSFC	Goddard Space Flight Center
HARPS	High Accuracy Radial velocity Planet Searcher
HD	Henry Draper catalog

HET	Hobby-Eberly Telescope
HIRES	HIgh-Resolution Echelle Spectrograph
HQ	Headquarters
HST	Hubble Space Telescope
HZ	Habitable Zone
IAC	Instituto de Astrofísica de Canarias
INT	Isaac Newton Telescope
IR	Infrared
IRAC	Infrared Array Camera
IRAS	Infrared Astronomical Satellite
IRS	InfraRed Spectrograph
IRT	Independent Review Team
IUE	International Ultraviolet Explorer
JCMT	James Clerk Maxwell Telescope
JHU	Johns Hopkins University
JKT	Jacobus Kapteyn Telescope
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KBO	Kuiper-Belt Object
Keck-I	Keck Interferometer
LBT	Large Binocular Telescope
LBT-I	Large Binocular Telescope Interferometer
LTSA	Long-Term Space Astrophysics theory program
MACHO	Massive Compact Halo Objects
mas	milli-arcsecond
μ as	micro-arcsecond
MIPS	Multiband Imaging Photometer for Spitzer
MIRI	Mid-Infrared Instrument
MIT	Massachusetts Institute of Technology
MOA	Microlensing Observations in Astrophysics
MOST	Microvariability and Oscillations of Stars
MPS	Microlensing Planet Search
NAI	National Astrobiology Institute
NASA	National Aeronautics and Space Administration
NED	NASA Extragalactic Database
NGST	Next Generation Space Telescope (see also JWST)
NICI	Near Infrared Coronagraphic Imager
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIR	Near Infrared
NIRCAM	Near Infrared Camera
NRA	NASA Research Announcement
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NStars	Nearby Stars Database Project
OGLE	Optical Gravitational Lensing Experiment
OHP	Observatoire de Haute Provence

APPENDIX D

OSS	Office of Space Science
PAL	Present Atmospheric Level
pc	Parsec
PGG	Planetary Geophysics and Geology
PI	Principal Investigator
PLANET	Probing Lensing Anomalies NETWORK
PMS	Pre-main-sequence
POP	Program Operating Plan
PSPC	Position Sensitive Photon Counters (for ROSAT)
PSF	Point Spread Function
R&A	Research & Analysis
RA	Right Ascension
RMS	Root Mean-Square
ROSAT	Röntgen Satellite (NASA)
ROSES	Research Opportunities in Space and Earth Sciences
RV	Radial Velocity
SCI	Structurally Connected Interferometer
SIRTF	Space Infrared Telescope Facility
SIM	Space Interferometry Mission
SIMBAD	Astronomical database (Centre de Données Astronomiques de Strasbourg)
SOFIA	Stratospheric Observatory For Infrared Astronomy
SOHO	SOLar and Heliospheric Observatory
Spitzer	Spitzer Space Telescope (formerly SIRTF)
STARE	Stellar Astrophysics and Research on Exoplanets
STEPS	Single Telescope Extrasolar Planet Survey
STEPSS	Survey for Transiting Extrasolar Planets in Stellar Systems
STIS	Space Telescope Imaging Spectrograph
STScI	Space Telescope Science Institute
SWG	Science Working Group
TEP	Transits of Extrasolar Planets network
TPF	Terrestrial Planet Finder
TPF-C	Terrestrial Planet Finder Coronagraph
TPF-I	Terrestrial Planet Finder Interferometer
UCLES	University College London Echelle Spectrograph
UC	University of California
UCO	University of California Observatories
URL	Universal Resource Locator
USNO	United States Naval Observatory
UV	Ultraviolet
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer
WMKO	W.M. Keck Observatory
XMM	X-ray Multi-mirror Mission

Appendix E

Further Reading

Terrestrial Planet Finder — News

Edited by R. Jackson (Jet Propulsion Laboratory)

http://planetquest.jpl.nasa.gov/TPF/tpf_news.cfm

NASA Research Opportunities

<http://research.hq.nasa.gov/research.cfm>

The Vision for Space Exploration

Sean O’Keefe, NASA Administrator (February 2004)

http://www.nasa.gov/pdf/55584main_vision_space_exploration-hi-res.pdf

A Renewed Spirit of Discovery

President George W. Bush (January 2004)

http://www.whitehouse.gov/space/renewed_spirit.html

Techniques and Instrumentation for Detection of Exoplanets

Edited by Daniel R. Coulter

SPIE Press: Bellingham, WA: Proc. SPIE 5170 (2003)

Towards Other Earths (Darwin/TPF)

Edited by B. Battrock

European Space Agency: ESA SP-539 (2003)

Technology Plan for the Terrestrial Planet Finder

Edited by C.A. Lindensmith

Jet Propulsion Laboratory, Pasadena, CA: JPL Pub 03-007 (2003)

http://planetquest.jpl.nasa.gov/Navigator/library/TechPlan_4-4-03RevA.pdf

Summary Report on Architecture Studies for the Terrestrial Planet Finder

Edited by C.A. Beichman, D.R. Coulter, C.A. Lindensmith, and P.R. Lawson

Jet Propulsion Laboratory, Pasadena, CA: JPL Pub 02-011 (2002)

http://planetquest.jpl.nasa.gov/TPF/arc_index.cfm

Origins Roadmap 2003

Origins Science Subcommittee

Jet Propulsion Laboratory, Pasadena, CA: JPL Pub 400-1060 (2002)

<http://origins.jpl.nasa.gov/library/roadmap03/>

Astronomy and Astrophysics in the New Millennium

National Academies Press (2001)

<http://www.nas.edu/bpa2/nsindex.html>

Biosignatures and Planetary Properties to be Investigated by the TPF Mission,

D.J. Des Marais et al,

Jet Propulsion Laboratory, Pasadena, CA: JPL Pub 01-008 (2001)

<http://planetquest.jpl.nasa.gov/TPF/TPFrevue/BioJun02.pdf>

TPF- A NASA Origins Program to Search for Habitable Planets

Edited by C.A. Beichman, N.J. Woolf, and C.A. Lindensmith

Jet Propulsion Laboratory, Pasadena, CA: JPL Pub 99-3 5/99 (1999)

http://planetquest.jpl.nasa.gov/TPF/tpf_book/index.cfm

A Road Map for the Exploration of Neighboring Planetary Systems

(Jet Propulsion Laboratory, Pasadena, CA: JPL Pub 96-22 8/96)

<http://origins.jpl.nasa.gov/library/exnps/index.html>